PTC/USER WORLD EVENT EUROPE, BERLIN 2002

miss it, miss out.

Designing for Six-sigma quality levels with Behavioral Modeling

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2002 WORLD EVENT
PTCuser
EUROPE, BERLIN

Outline

What it's NOT

A flashy sales demo of Behavioral Modeling

A complex statistical analysis presentation

What it is

- A status of the current design and simulation state in the product development process
- Overview of the tools and techniques for traditional and robust design (DOE, PDS, BMX, Six-sigma, design synthesis, etc)
- An overview of the "Engineering Quality into the Design"
- Implementation examples of Behavioral Modeling
- Overview of the implementation challenges and solution strategies to overcome them

Acknowledgments

The author would like to recognize his colleagues at:

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NAE / NASA Study on product development

DOE Office of Transportation Technologies (DFV)

NREL Center of Transportation Technologies & Systems

FORD Motor Company (CAE Methods Development Group)

NASA Ames (Integrated Systems Technologies Branch)

for their financial support and technical contributions and source of information

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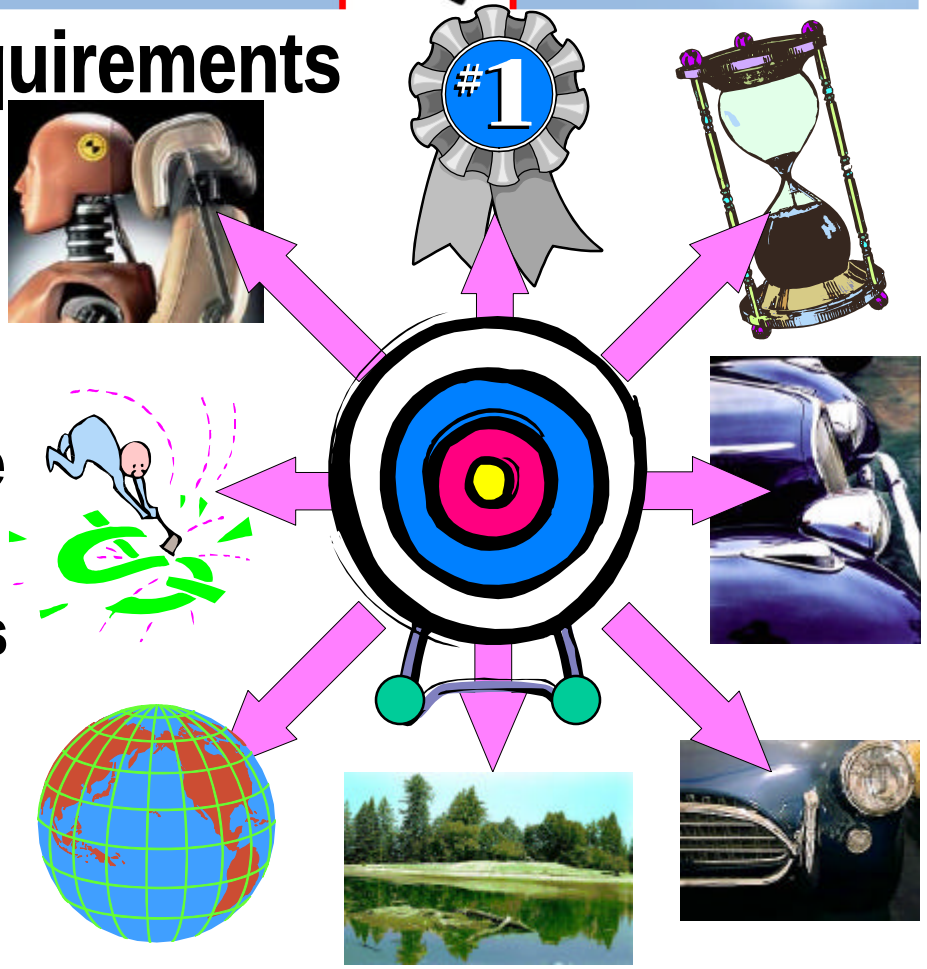
Contradicting Design Requirements

- Cost
- Performance & safety
- Quality
- Time to market & short life cycle
- Environmental impacts
- Wow Aesthetics (creating waves of lust for the product, I got to have it ...)
- Major Changes in Industry's Business Model



Changes in Automotive Industry's Business Model

- Cycle development time from concept to production is being compressed significantly
  - 1992: 60 months
  - 1996: 48 months
  - 2000: 18 months
- Vehicle designs are tailored to focused markets
- Vehicles are being manufactured more on a global scale
- Vehicles designed increasingly through multiple engineering sites around the world
- Need for enabling companies throughout the supply chain and extended enterprise to share information through a web-centric visualization approach

Elements in Product Development Process

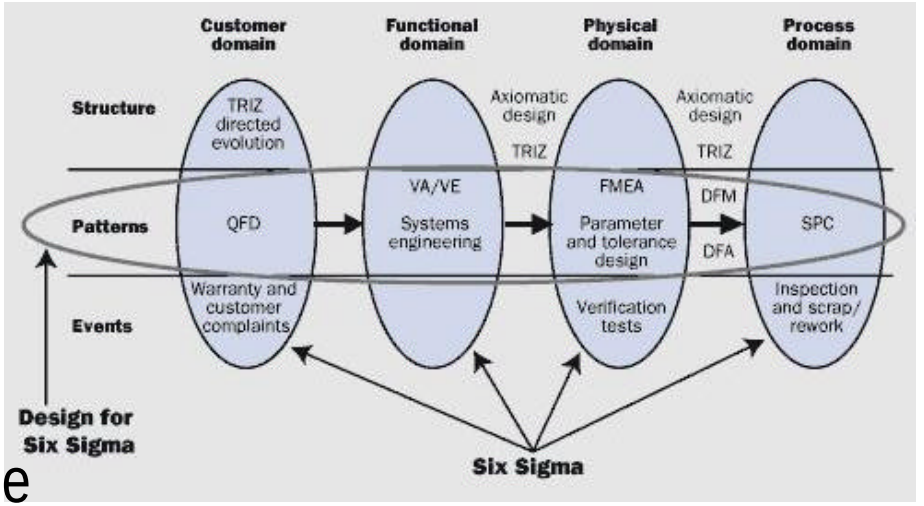
Concept Development

Product Design

Attribute Refinement

Design information systems

- Knowledge capture and reuse
- Documentation of rationale for the design
- Self designed parts
- Collaborative design



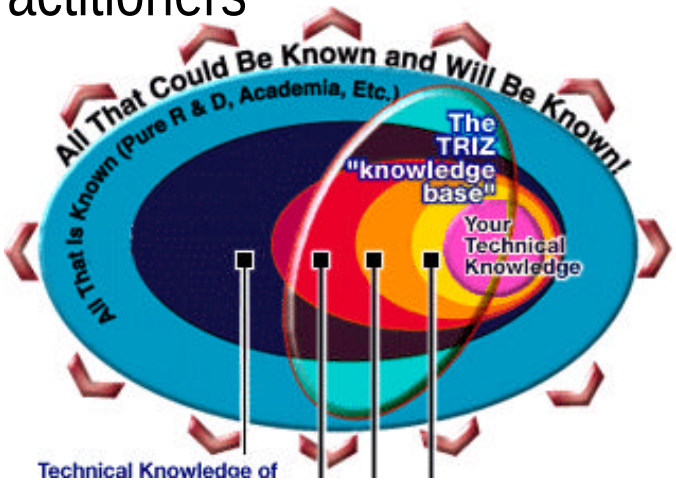
Concept Development

Typical Elements Today

- Conceptual design generation is highly iterative & mostly manual
- Inconsistent use of heuristics, rules of thumb
- Success requires experienced skilled practitioners

Possible Today

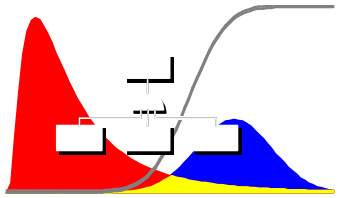
- TRIZ, Functional Diagrams
- Material-process-section selector
- Topology optimization
- Rapid Prototyping



Elements of Product Design

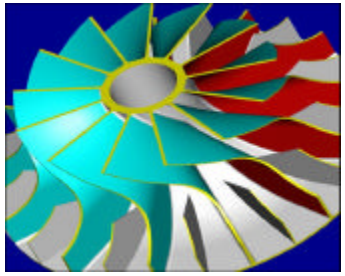
- Rapid generation of design alternatives (CAD, tolerance / variational analysis)
- Process is CAD centric and highly iterative
- Easy evaluation of candidate designs (FEA, CFD, Multi-physics)
- Rigorous evaluation and comparison of design alternatives
- Nonsystematic decision making, many design decisions are based on aggregation of preferences
- Limited reuse of product designs
- Success requires experienced skilled practitioners

Attribute Refinement



Typical Elements

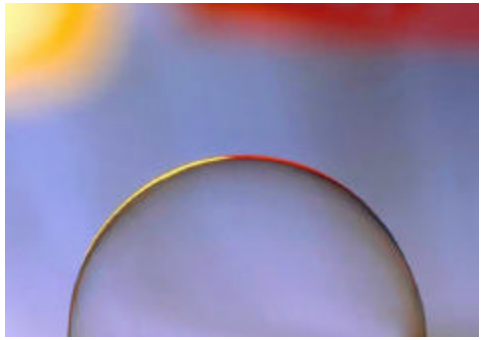
- More than half of attributes require experimental refinement
- Physical prototypes required



Possible Today

- Sensitivity and optimization studies of designs
- Robust Designs (DOE, BMX, PDS, Six-sigma)
- Reliability based optimization

Expectations of CAD & CAE implementation



- Reduced Prototypes and testing
- Better integration with suppliers
- Increased reuse of existing designs
- Early prediction of product attributes
- More program predictable results
- Knowledge capture and reuse

Results of CAD & CAE implementation

- Sporadic demonstrations not sustained benefits
- Best reduction in design and development cost 75% with 2x product complexity
- Typical reduction in design and development cost 5-10% with 2-3x product complexity
- Still tradition and experience govern the design choices

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Quality - Robust Design

Definition of Robust Design:

Deliver customer expectations at profitable cost regardless of:

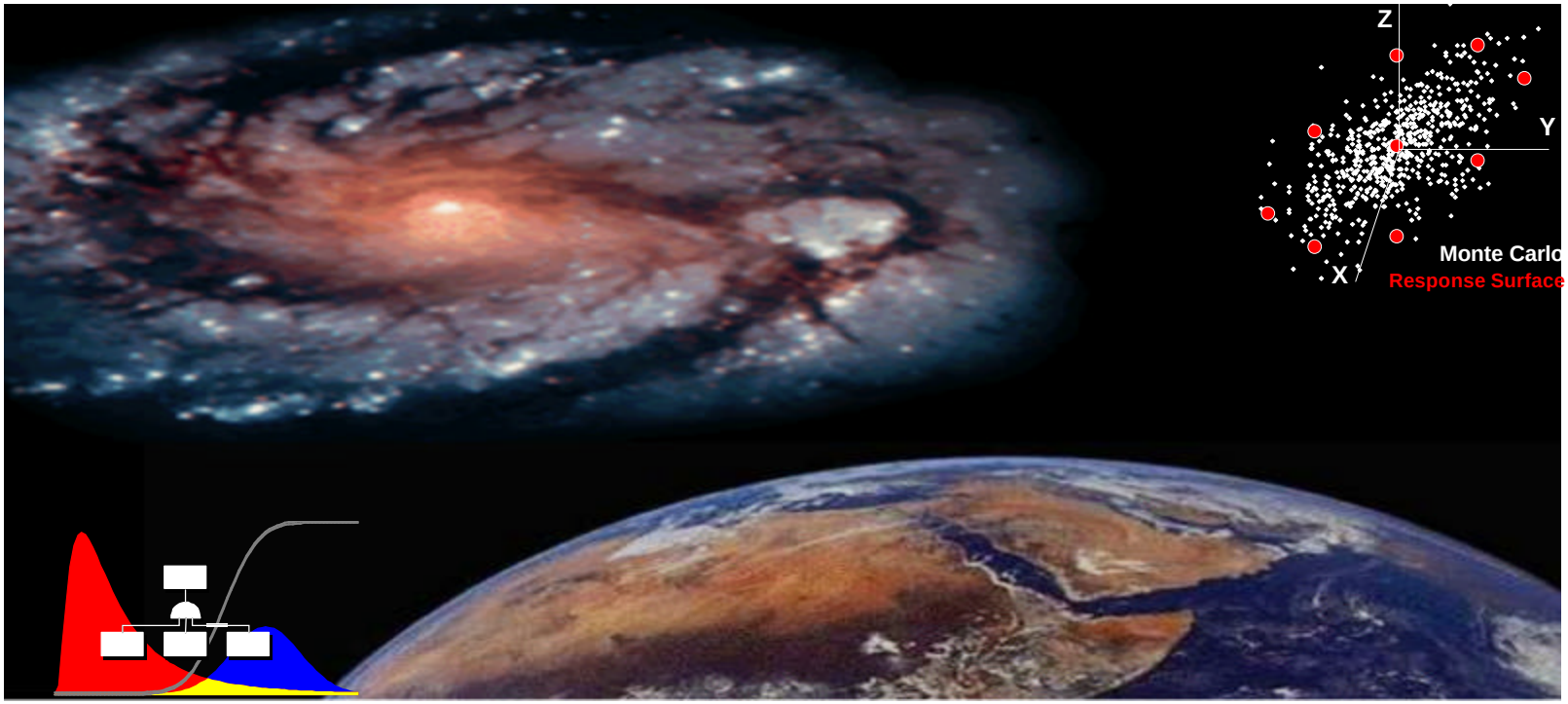
- customer usage
- variation in manufacturing
- variation in supplier
- variation in distribution, delivery & installation
- degradation over product life

Goals of Robust Design (shift and squeeze)

- Shift performance mean to the target value
- Reduce product's performance variability

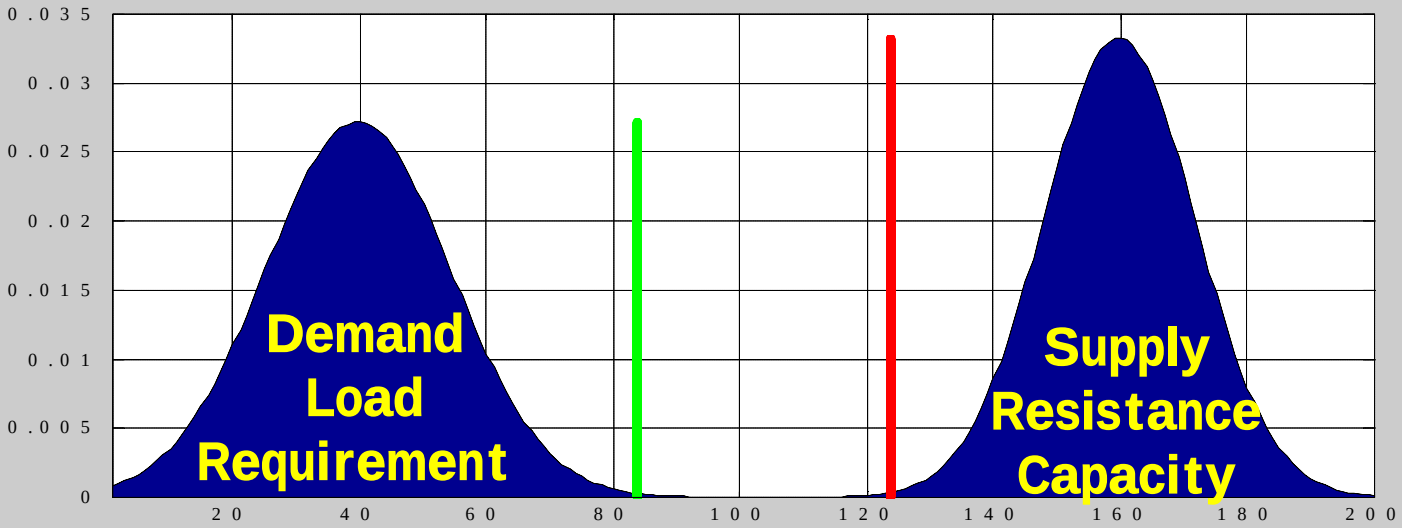
Randomness and Scatter is a part of reality Everywhere

Probabilistic Design Techniques bring simulation closer to REALITY!



Traditional Deterministic Approach

- **Accounts for uncertainties through the use of empirical Safety factors:**
  - Are derived based on past experience
  - Do not guarantee safety or satisfactory performance
  - Do not provide sufficient information to achieve optimal use of available resources



Statistical Design Performance Simulation

" You 've got to be passionate lunatics about the quality issue ..."

Jack Welch

" Product quality requires managerial, technological and statistical concepts throughout all the major functions of the organization ..."

Josheph M. Juran

Variation (thickness, properties, surface finish, loads, etc.) is ... ***THE ENEMY***

DOE, Six Sigma, Statistical FEA, Behavioral Modeling ... ***THE DEFENCE***

Tools for Robust Design

Design Of Experiments (DOE)

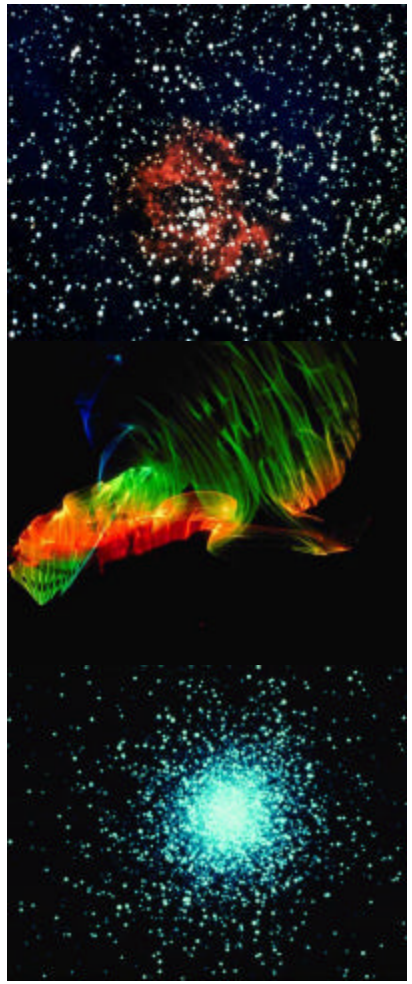
- Exploits nonlinearities and interactions between noise & control parameters to reduce product performance variability
- full factorial, fractional factorial, Monte-Carlo, LHC

Response Surface Methods

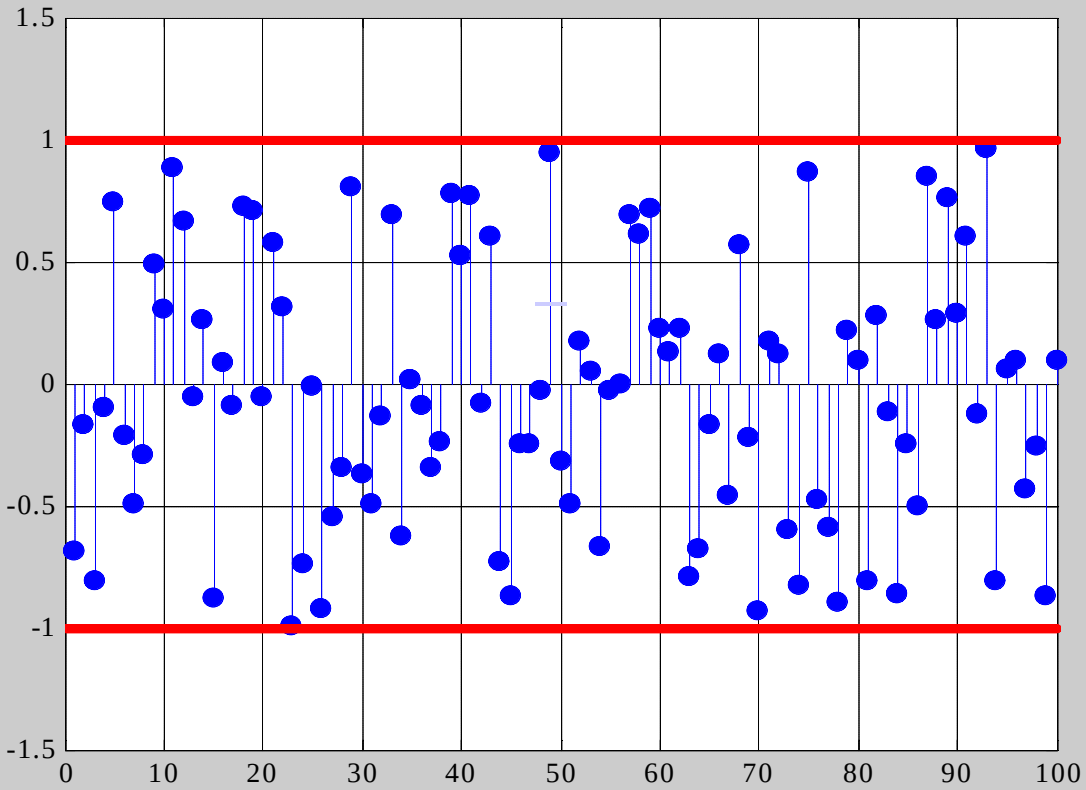
- Central Composite Design
- Box-Behnken Design

6-sigma design (Statistical Performance)

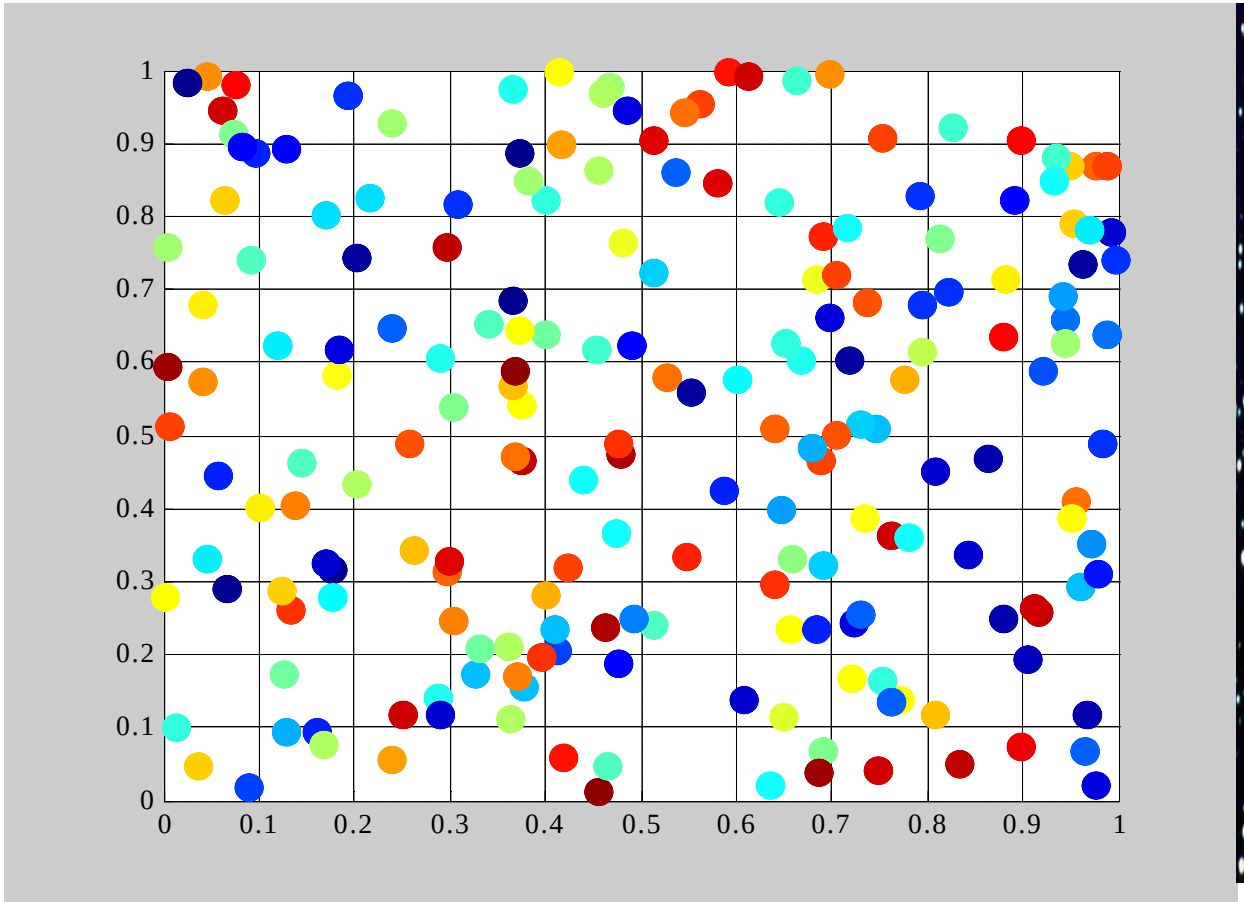
- Identifying & qualifying causes of variation
- Centering performance on specification target
- Achieving Six Sigma level robustness on the key product performance characteristics with respect to the quantified variation



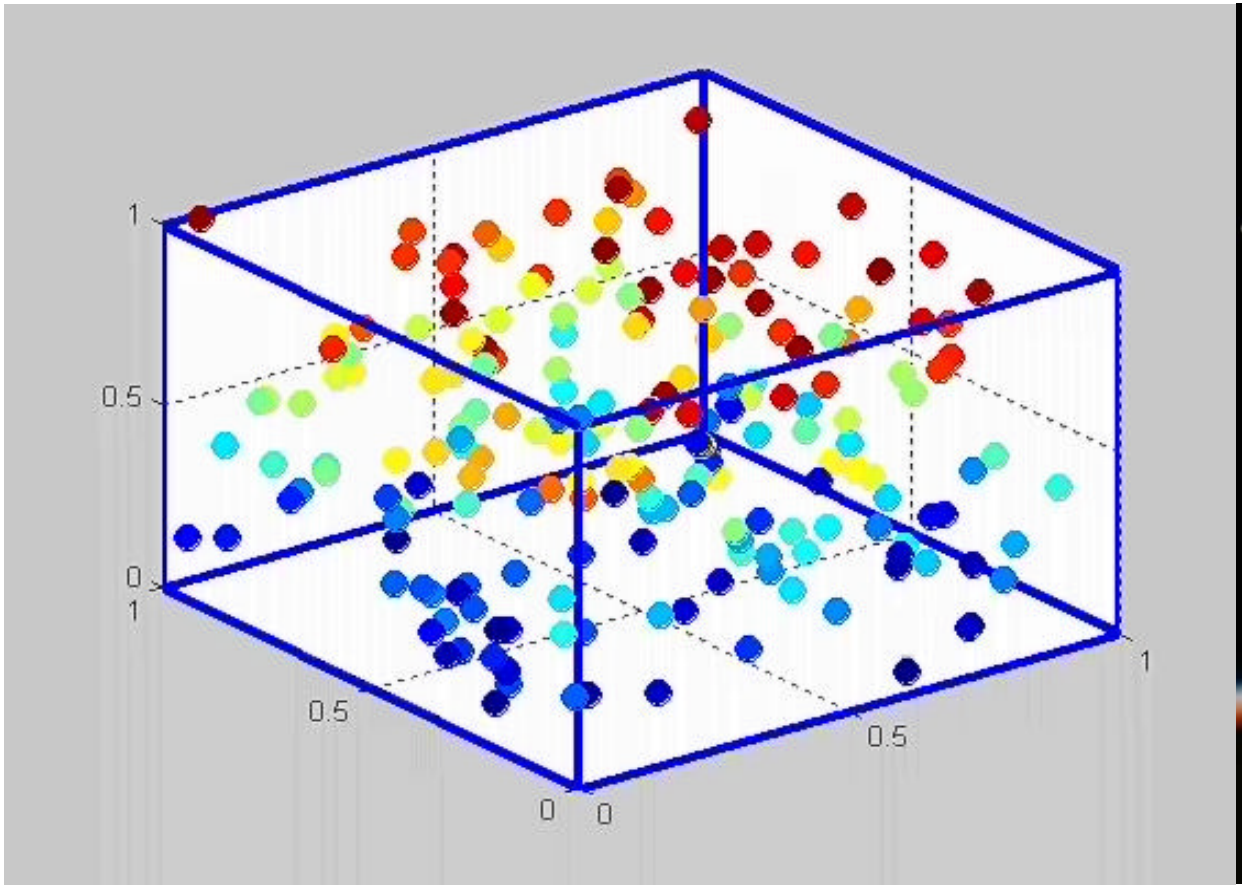
Design Space Exploration 1 Variable



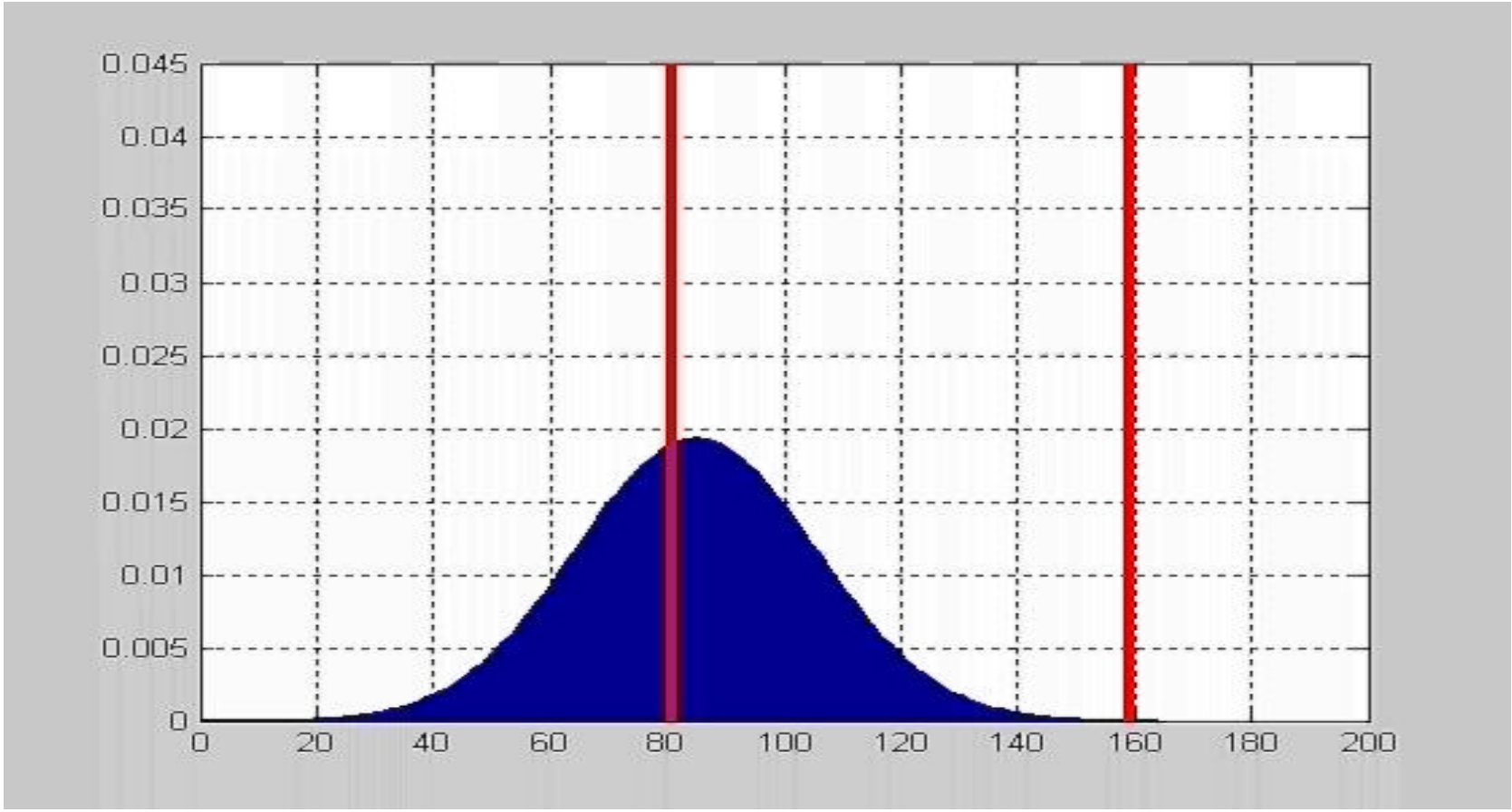
Design Space Exploration 2 Variables



Design Space Exploration 3 Variables



Statistical Performance: Shift and Squeeze



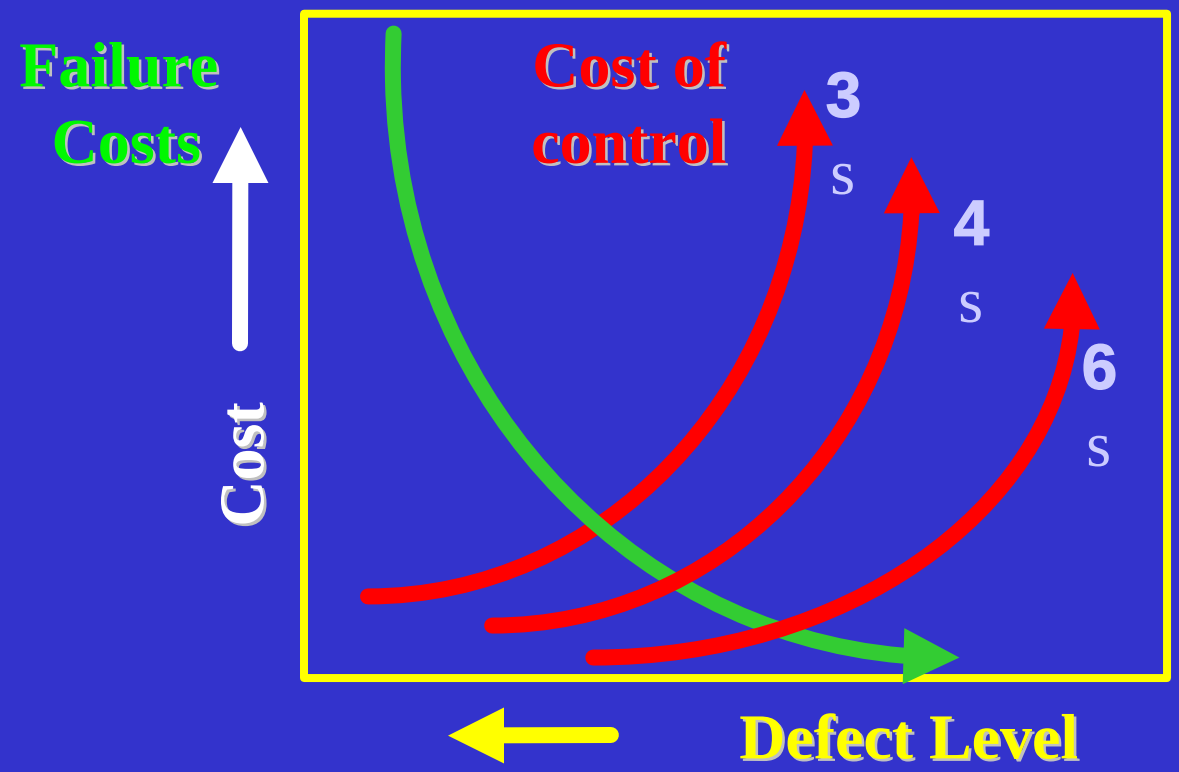
Improved Quality Reduced Total Cost

Cost of Defect or Failure

- Lost Customers
- Liability
- Recalls
- Rework

Examples:

- Titanic
- Asbestos
- Breast Implants
- Bhopal, India



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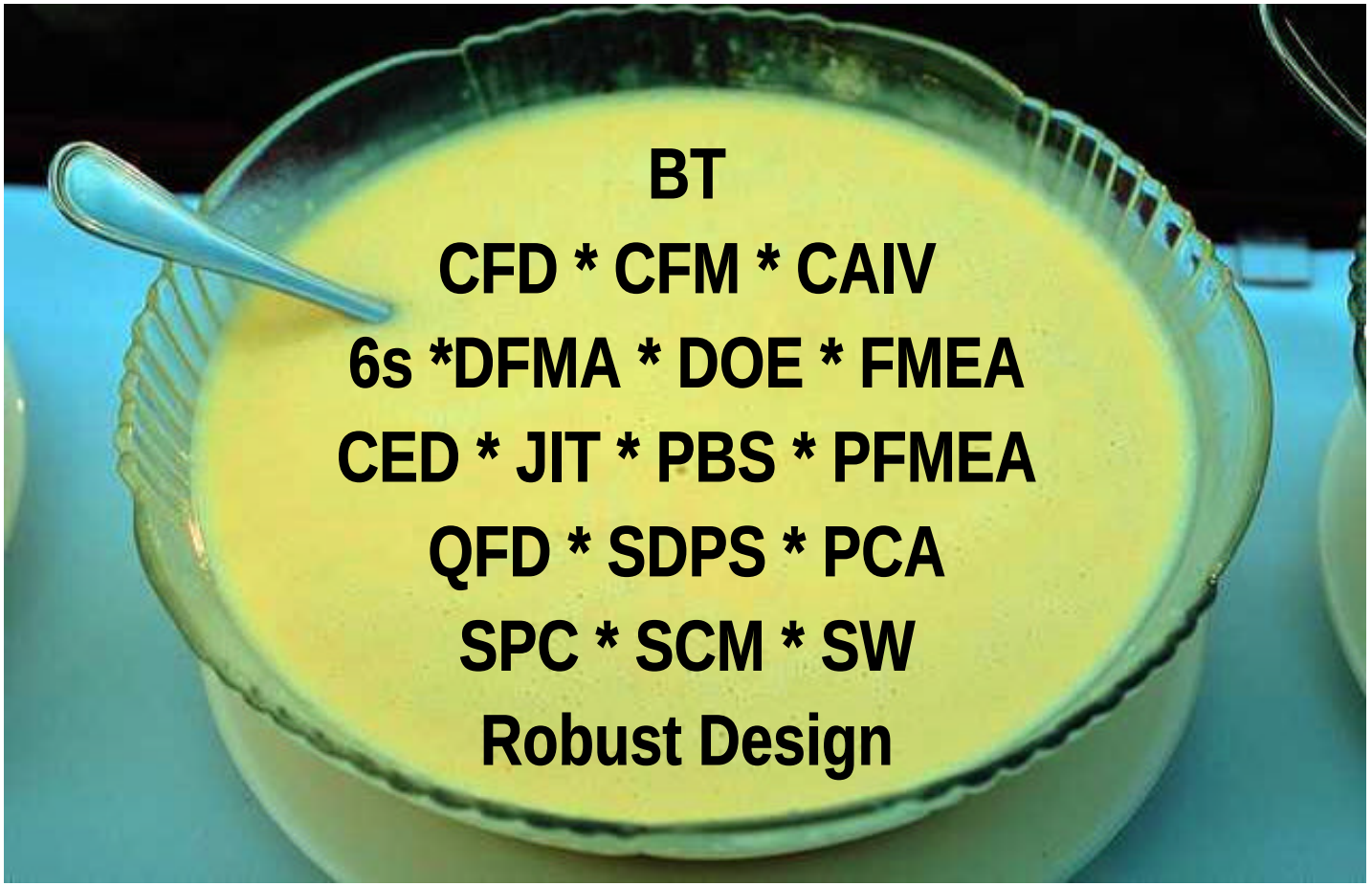
Elements of Quality Management Process

- Agile Improvement Process
- Axiomatic Design
- Benchmarking & Bench-trending
- Catch-ball
- Cellular Manufacturing
- Continuous Flow Development
- Continuous Flow Manufacturing
- Cycle Time Management
- Defect Reduction
- Design for Manufacturing and Asm.
- Design of Experiments
- Failure Modes Effects Analysis
- Cause and Effect Diagrams
- Just In Time
- Performance Based Specifications
- Process Failure Mode Effects Analysis
- Quality Function Deployment
- Robust Design
- Self-Directed Work Teams
- Statistical Design Performance Simulation
- Process Capability Analysis
- Statistical Process Control
- Supply Chain Management
- Synchronous Workshops
- Theory of Constraints
- Thinking Process Reality Trees
- Total Productive Maintenance

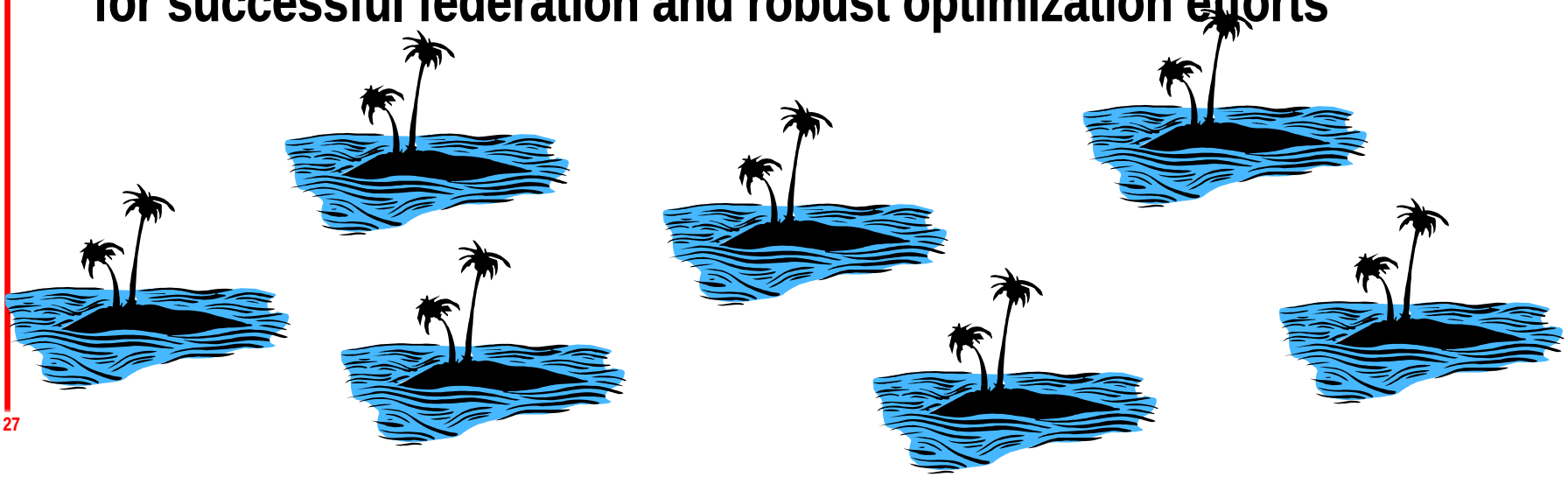
Elements of Quality Process: The alphabet soup



Elements of Quality Management Process

Although all the elements of quality management process are closely connected they remain apart because they have been developed independently from each other

Integration of these tools is critical to the organization and necessary for successful federation and robust optimization efforts

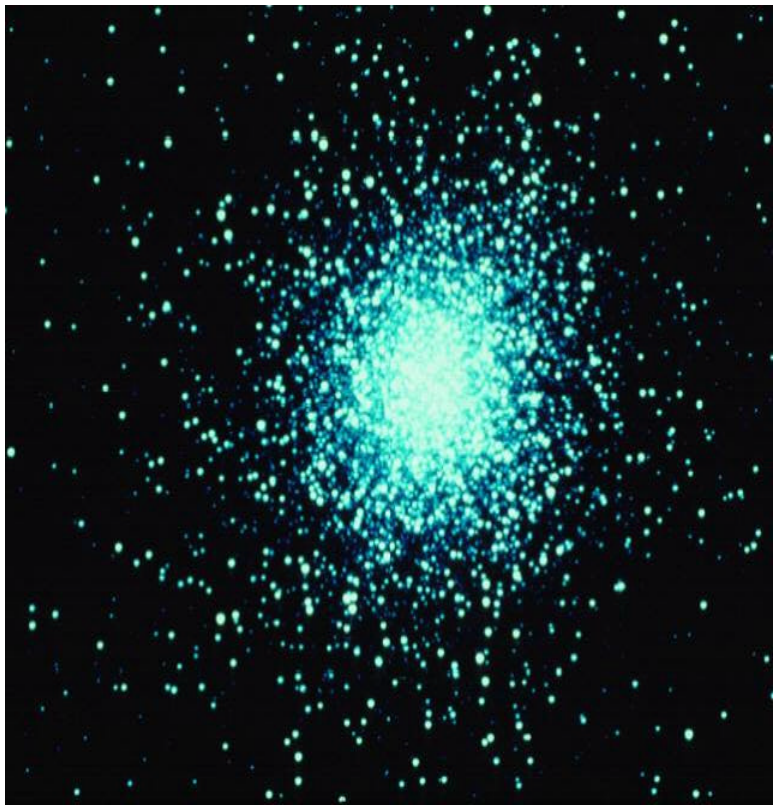


Identifying Noise & Control Parameters

Noise parameters:

Factors that are beyond the control of the designer

- material property variability
- manufacturing process limitations
- environment temperature & humidity
- component degradation with time
- ...



Control Parameters:

Factors that the designer can control

- geometric design variables
- material selections
- design configurations
- manufacturing process settings
- ...

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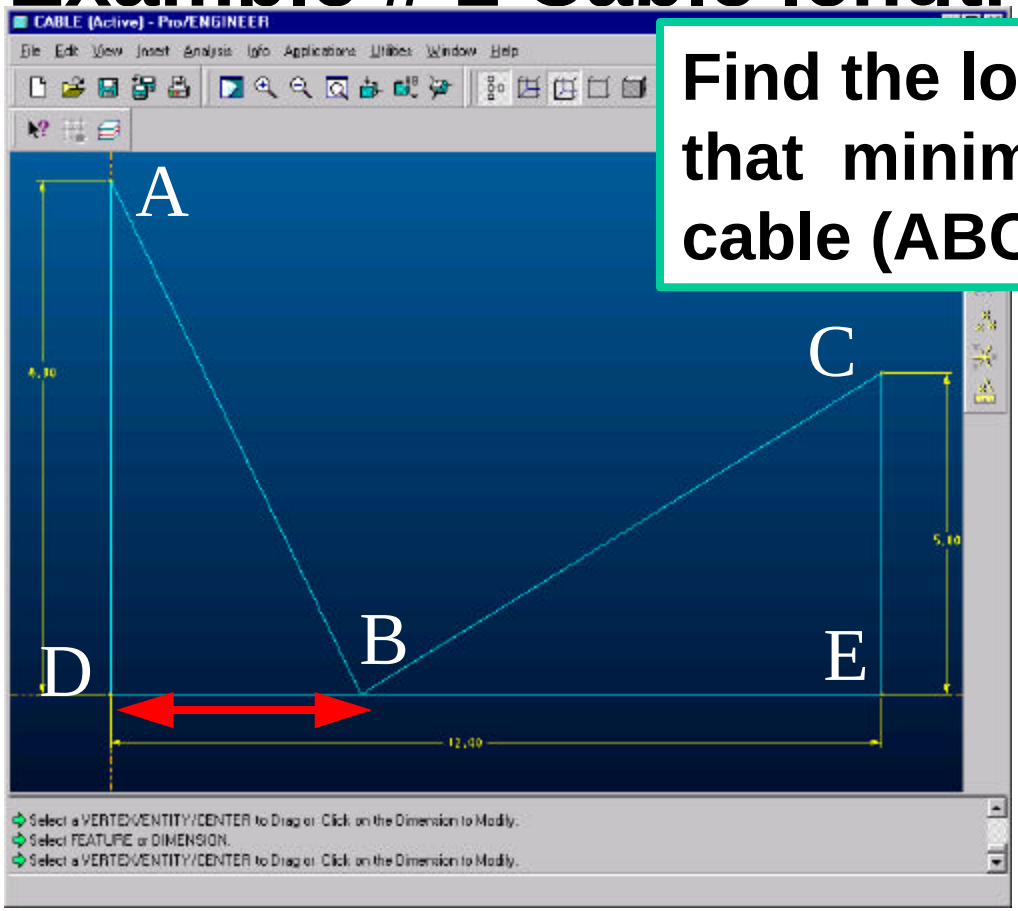
Implementation Examples of Behavioral Modeling

1. Cable length optimization
2. Requirement Driven design
3. Inspection of thickness requirements in castings
4. Packaging optimization of metal stamped parts to minimize scrap
5. Robust container design
6. Reliability based design within Pro/Engineer

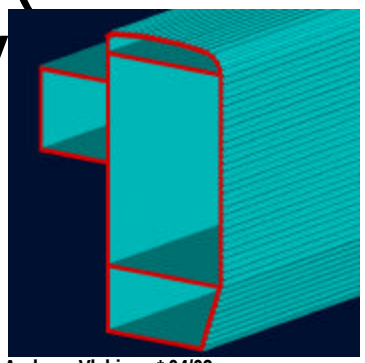
Example # 1 Cable length minimization



Find the location (distance DB) that minimizes the length of the cable (ABC).

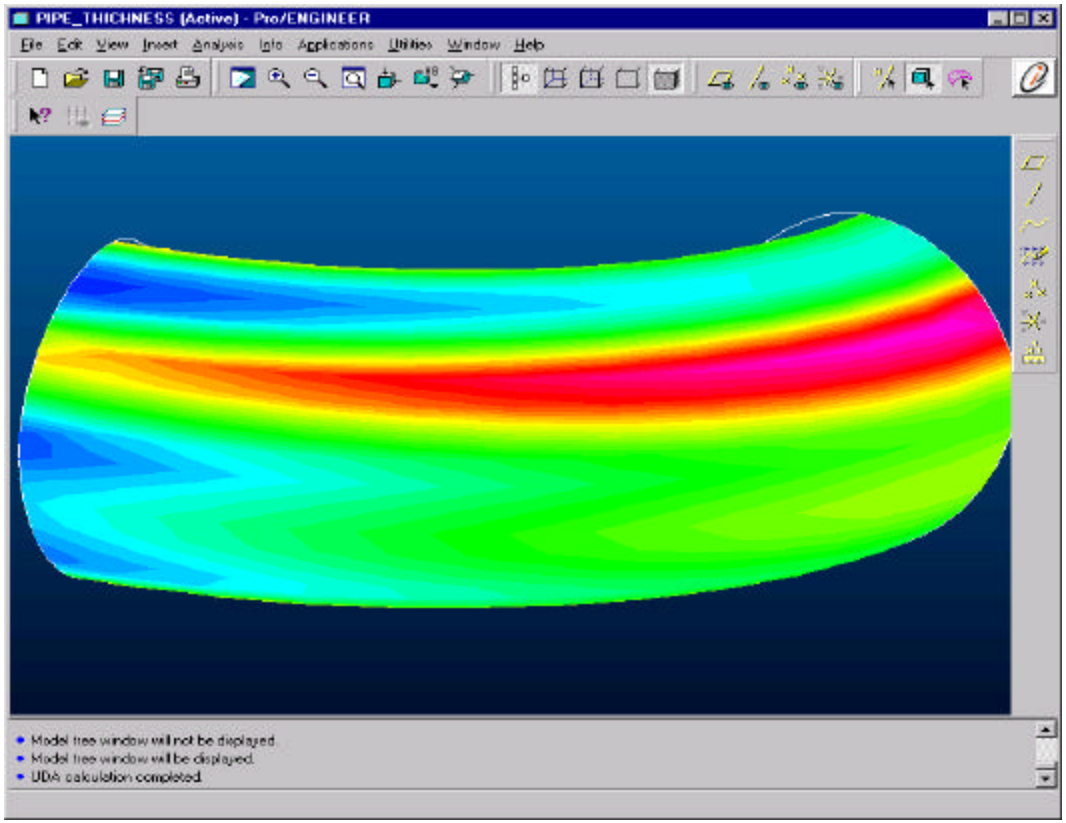
Example # 2 Behavioral Modeling of the Section

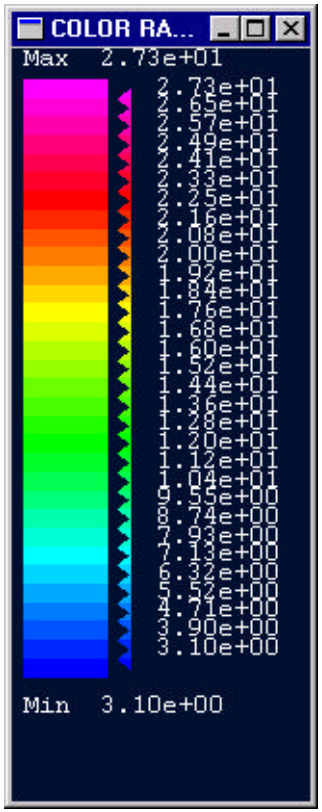
- All sections have the same moment of Inertia
- Find the one that minimizes the cross sectional area (Min Weight) and meets all the manufacturing and stability requirements
- Not a dimension driven CAD model
- Requirement driven design (I_{req})



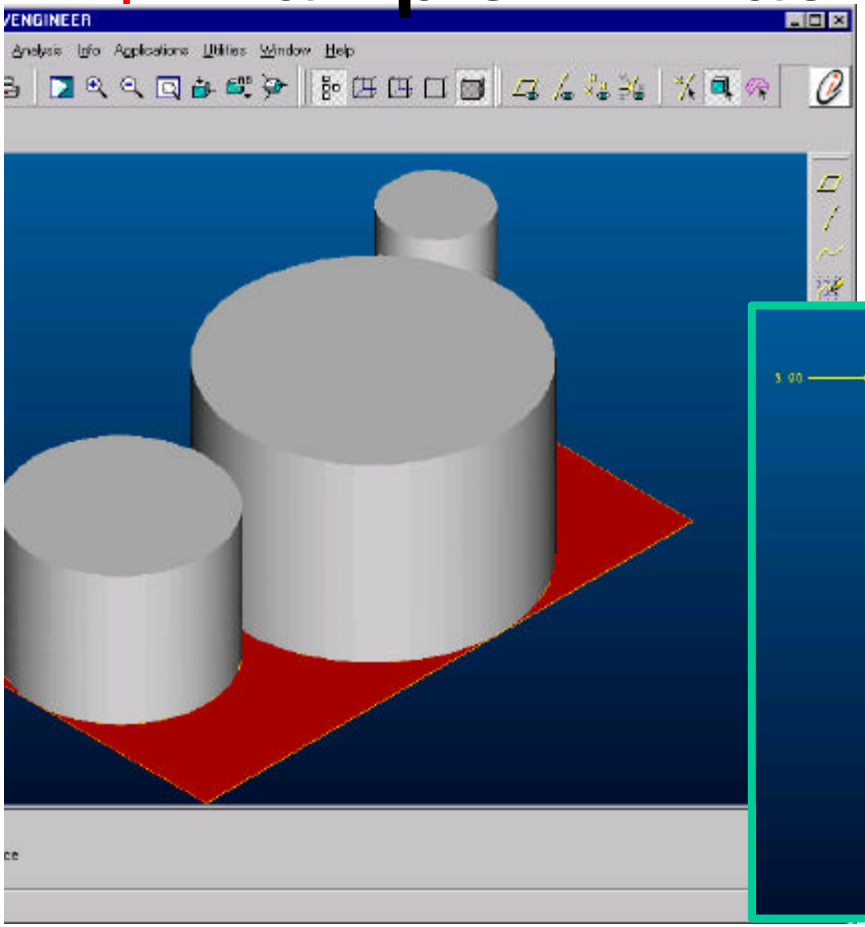
Example # 3 Thickness Distribution

Inspect the cast pipe for minimum thickness requirement



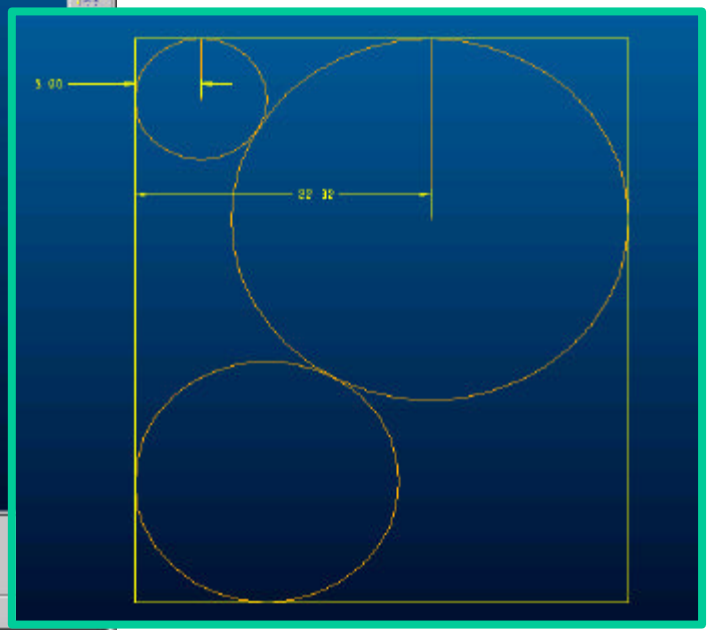


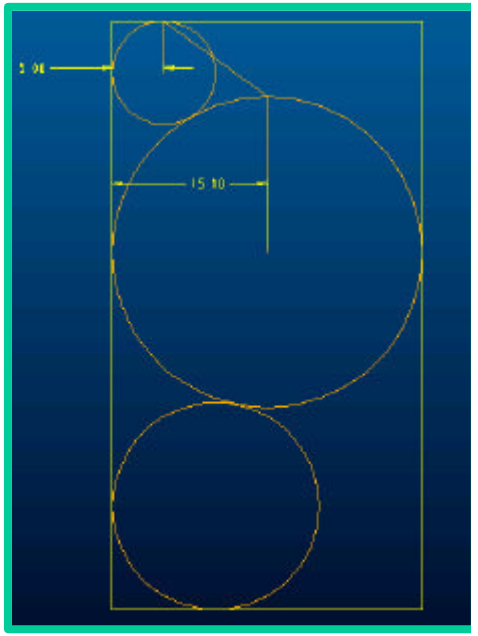
Example # 4 Packaging Optimization



Arrange the objects such that the circumscribed rectangle has:

- **minimum projected area**
- **minimum perimeter**
- **minimum container surface area**





Example # 5 Robust container design

What values of D and H give the least variation (robust Design) in Volume V?

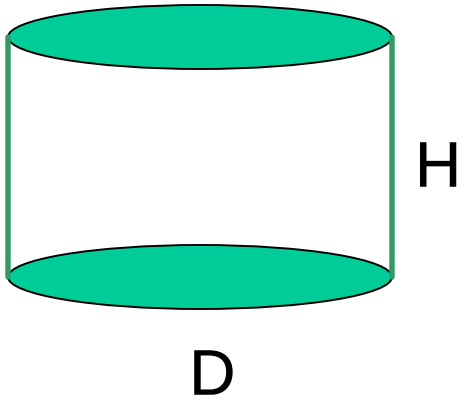
The desired volume is V= 300

The standard deviation in H and D is 0.5

3 < D < 10

7 < H < 14

Using Behavioral Modeling Build a part that automatically selects D, H to produce a design with the desired volume and the least volume variation (robust design)



Traditional Solution A: Derivative Optimization

$$V(H, D) = \pi D^2 H / 4$$

$$\sigma_H = 0.5, \ \& \ \sigma_D = 0.5$$

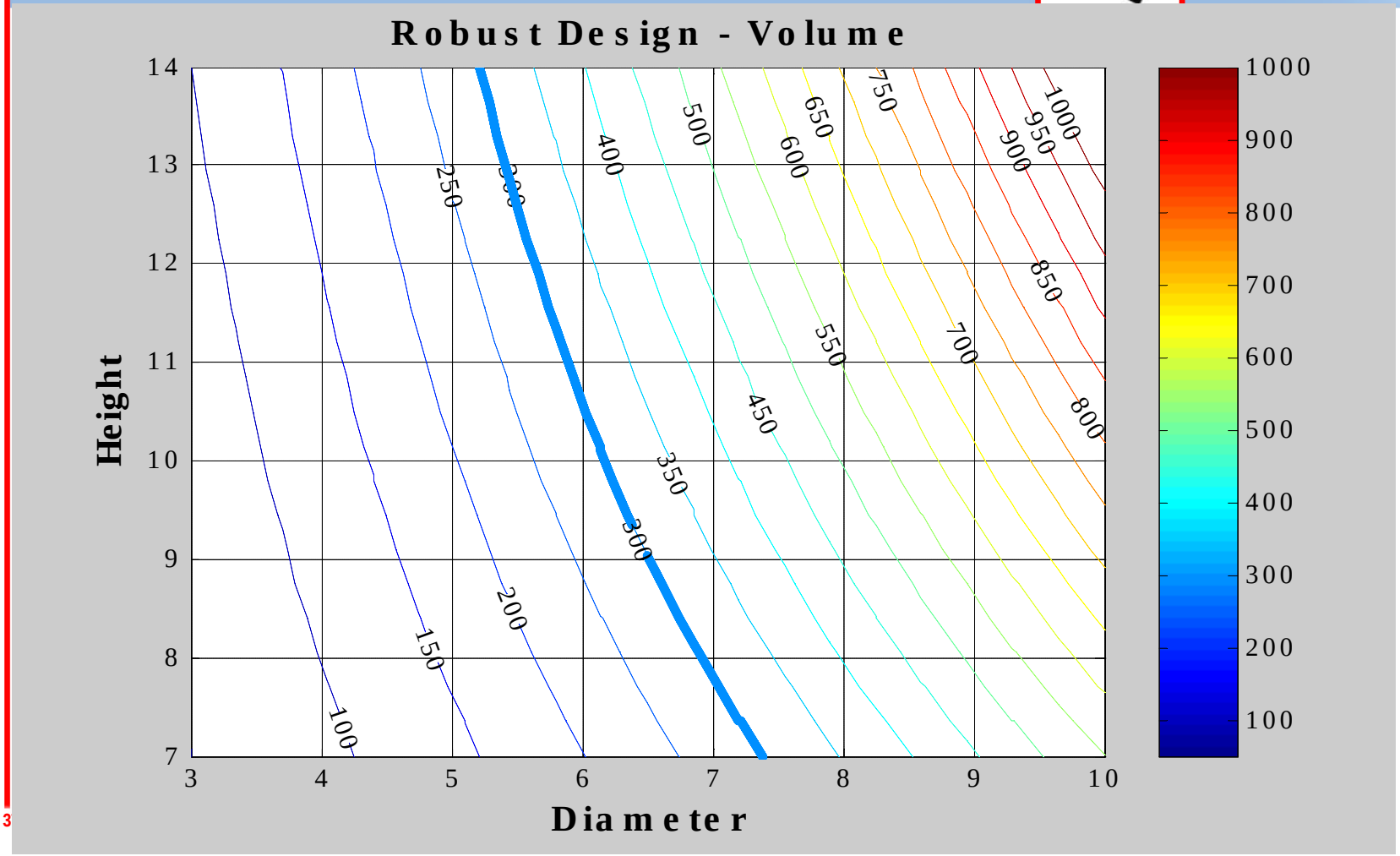
Volume variance approximation:

$$\sigma_v = (V,_D)^2 (\sigma_D)^2 + (V,_H)^2 (\sigma_H)^2$$

$$\sigma_v = (\pi D H / 2)^2 (\sigma_D)^2 + (\pi D^2 / 4)^2 (\sigma_H)^2$$

Optimization setup:

- Minimize σ_v
- Constraint V=300
- Design variables:
  - $3 < D < 10$
  - $7 < H < 14$


Robust Design - Volume
Height
Diameter
14
13
12
11
10
9
8
7
3
4
5
6
7
8
9
10
100
150
200
250
300
350
400
450
500
550
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300
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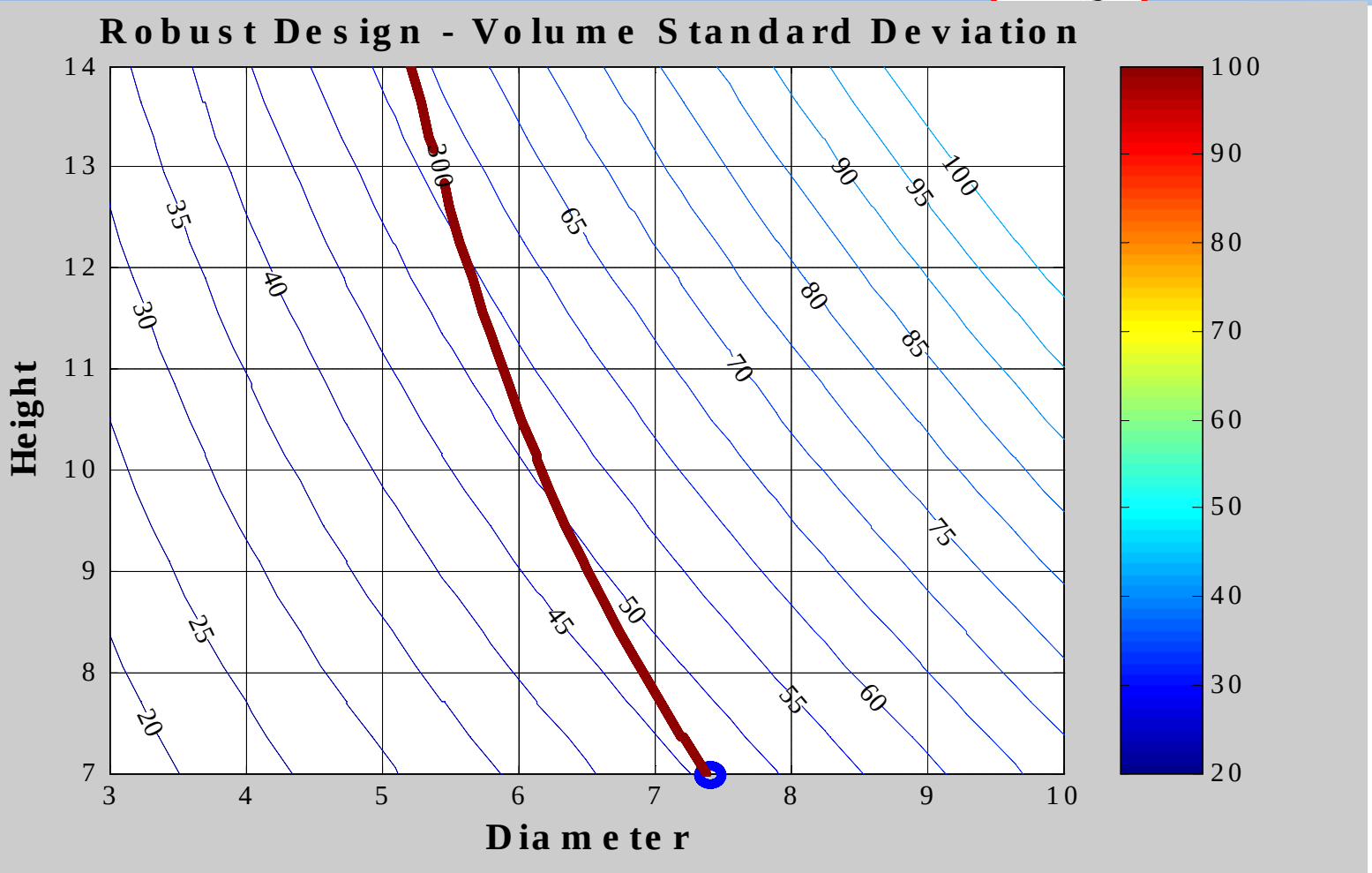
100


Robust Design - Volume Standard Deviation
Height
Diameter
14
13
12
11
10
9
8
7
3
4
5
6
7
8
9
10
300
35
40
30
65
90
95
100
80
85
70
75
50
45
25
20
55
60
100
90
80
70
60
50
40
30
20

Traditional Solution B: Monte Carlo Sampling

Generate sample points that have normal distribution with trial means i,e :

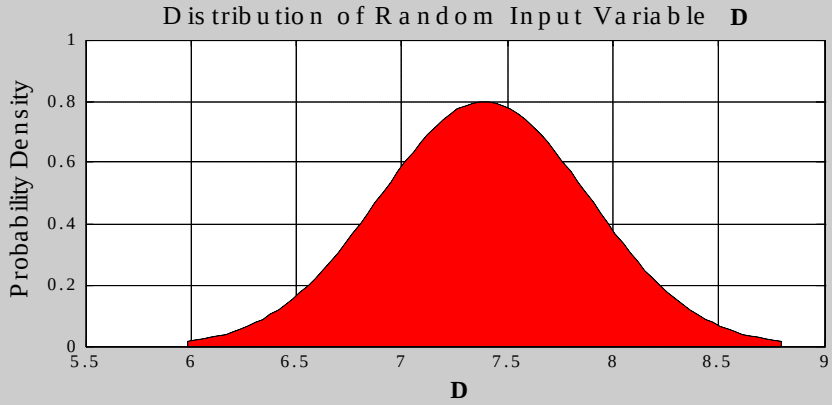
$$m_D = 7.39 \;\&\; s_D = 0.5$$

$$m_H = 7.00 \;\&\; s_H = 0.5$$

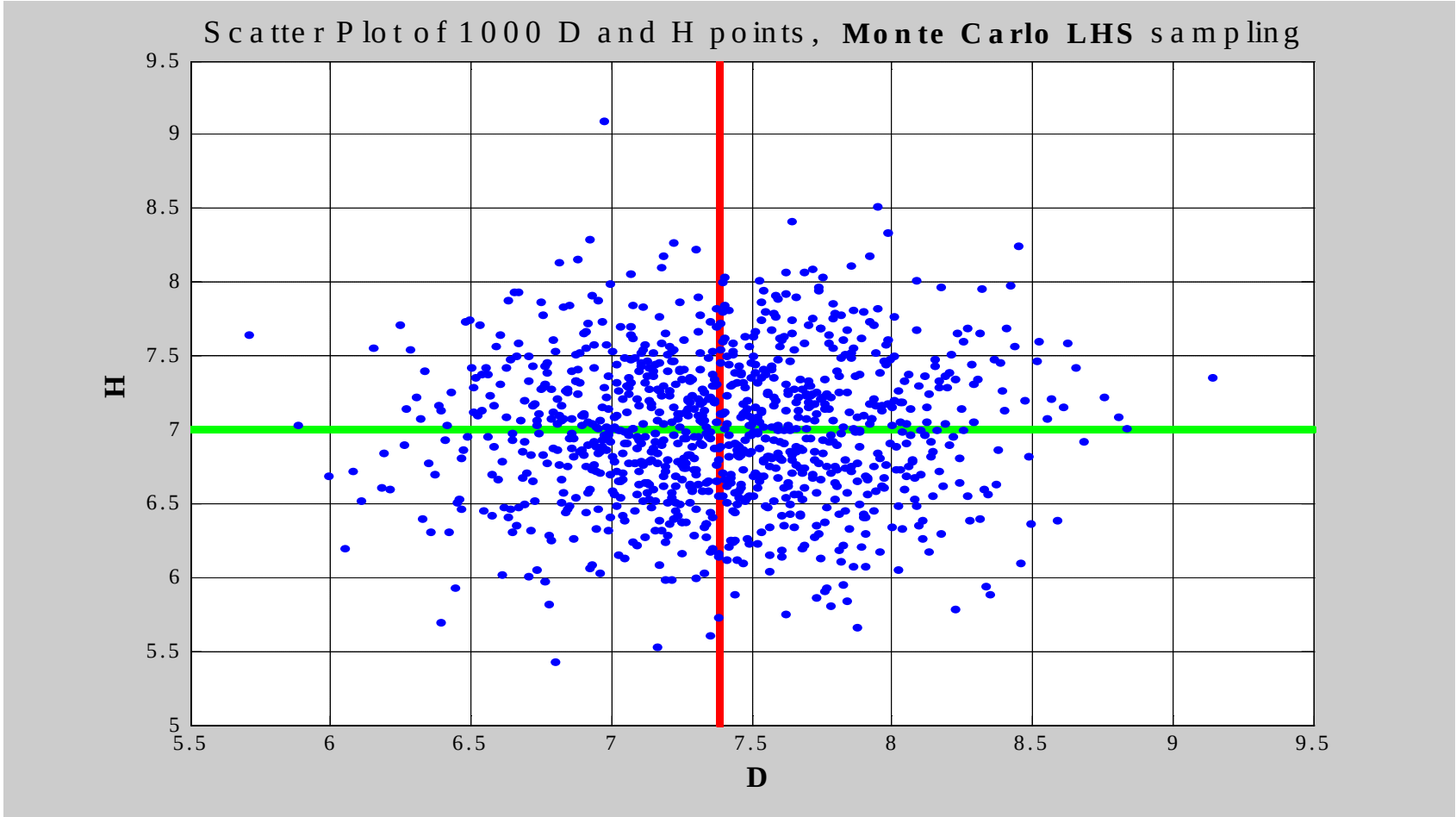
Use Monte Carlo direct or Latin Hyper-Cube Sampling techniques to generate pairs of D, H

Compute Volumes

Compute Standard deviation



Scatter Plot of 1000 D and H points Monte Carlo LHS sampling



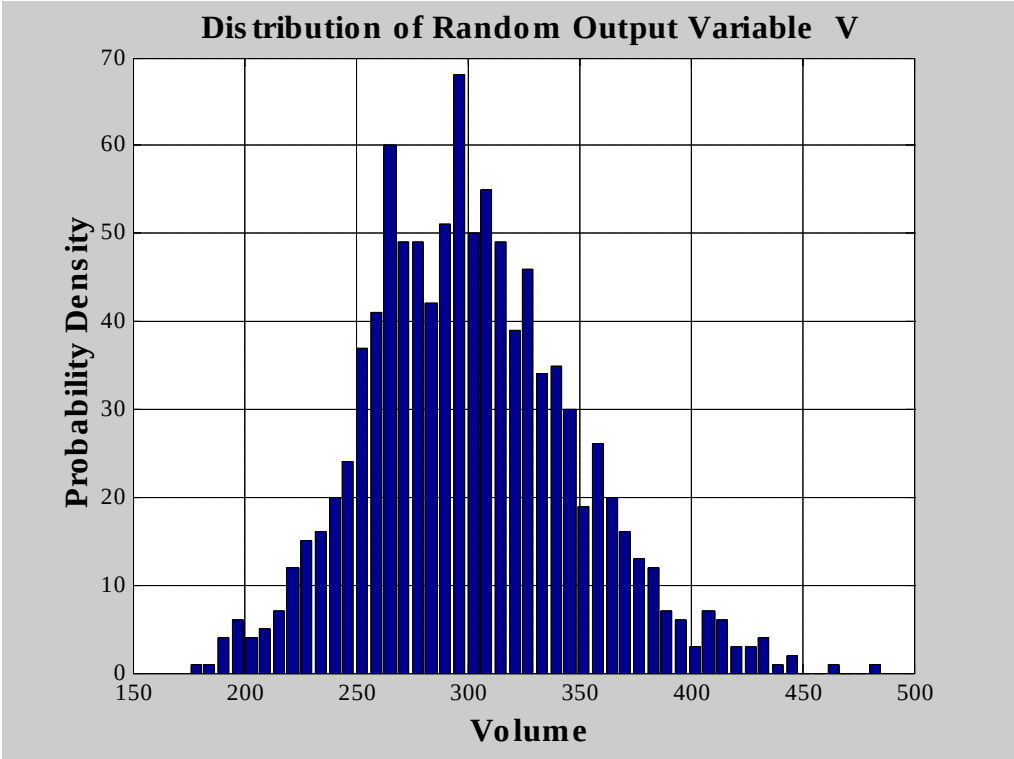
Random Distribution of Volume

Solution that minimize σ_V:

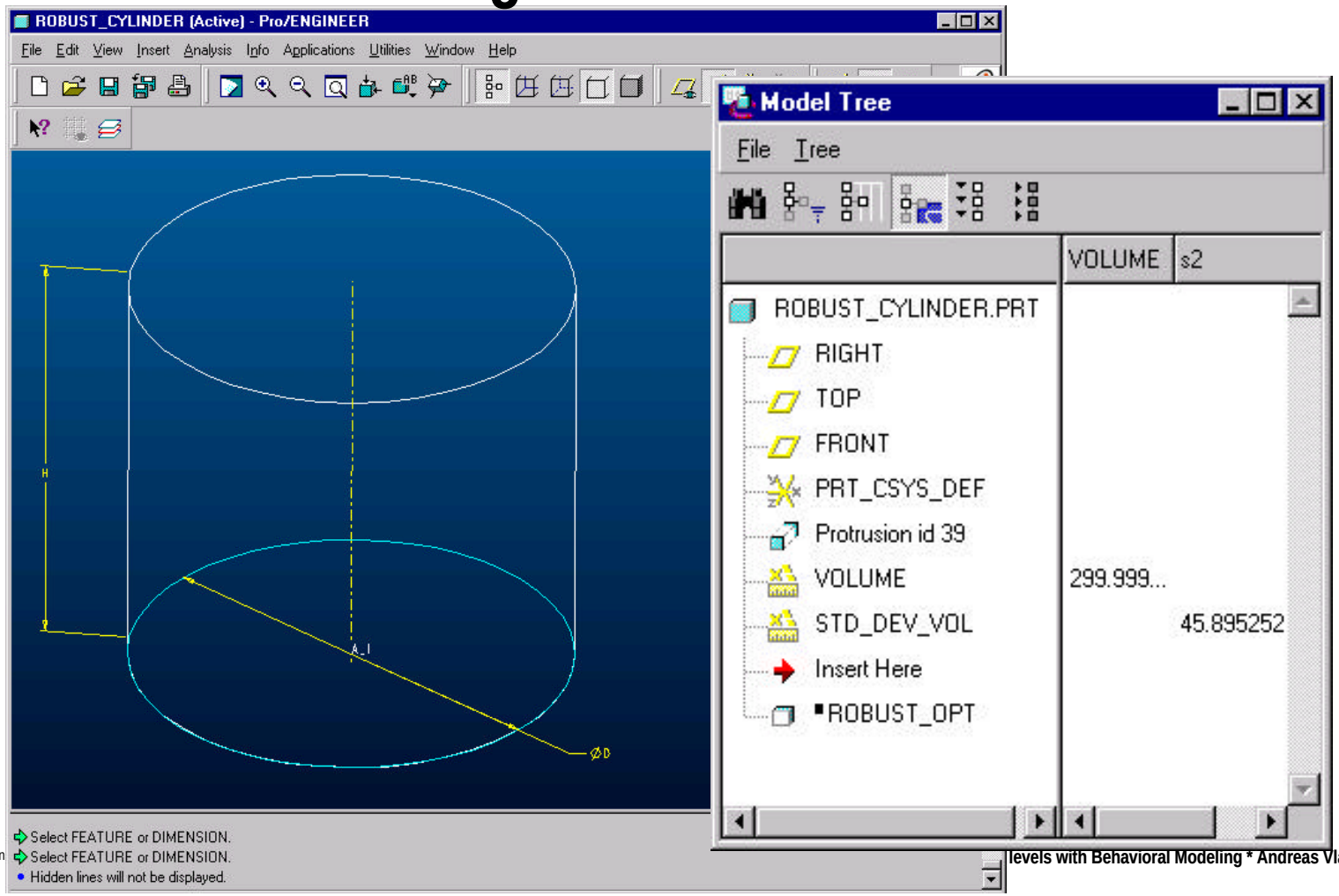
- $m_D = 7.39$
- $m_H = 7.00$

With

- $s_V = 46.87$
- $m_V = 300.1$



Behavioral Modeling Solution: Automation of Robust Design



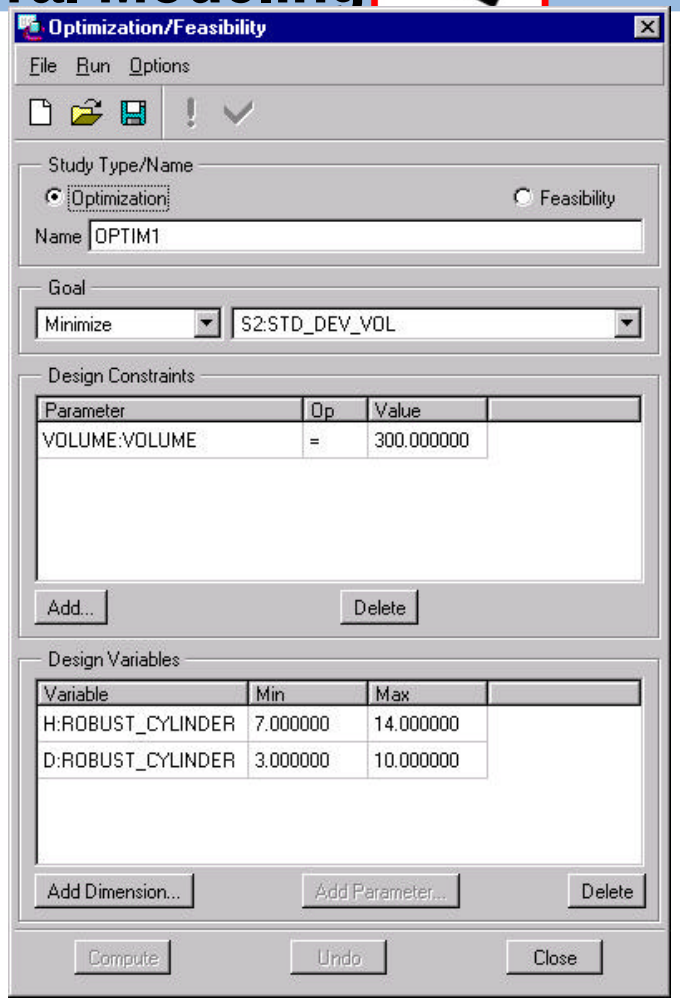
Robust Design with Behavioral Modeling

Optimization setup:

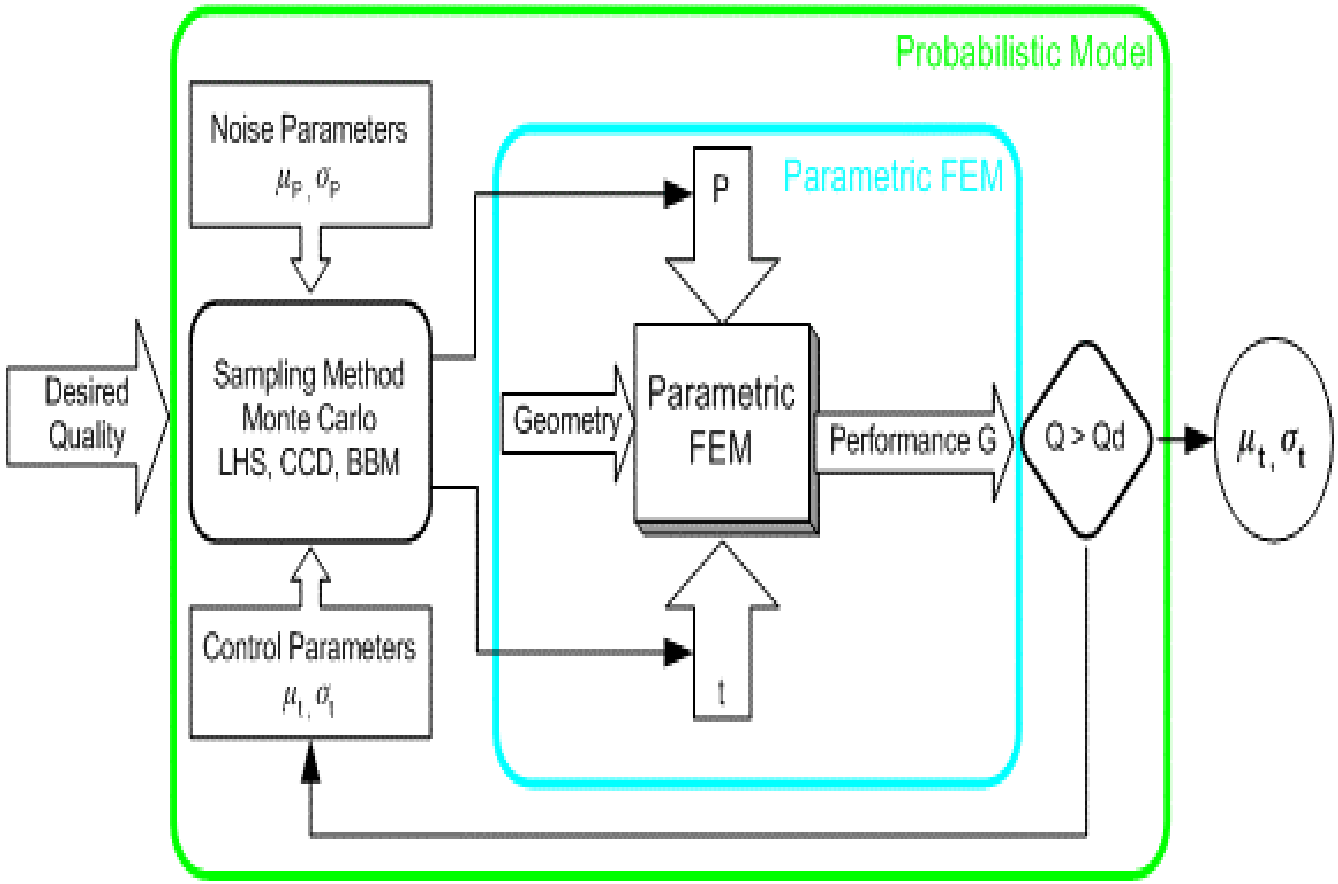
- Minimize σ_v
- Constraint V=300
- Design variables:
  - 3 < D < 10
  - 7 < H < 14

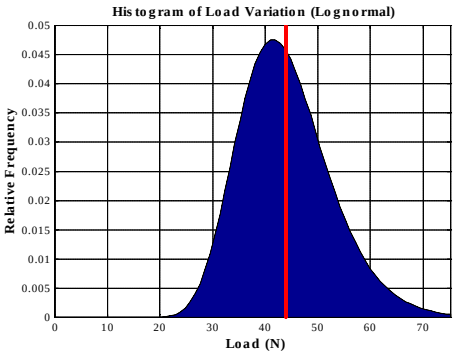
Solution that minimize σ_v:

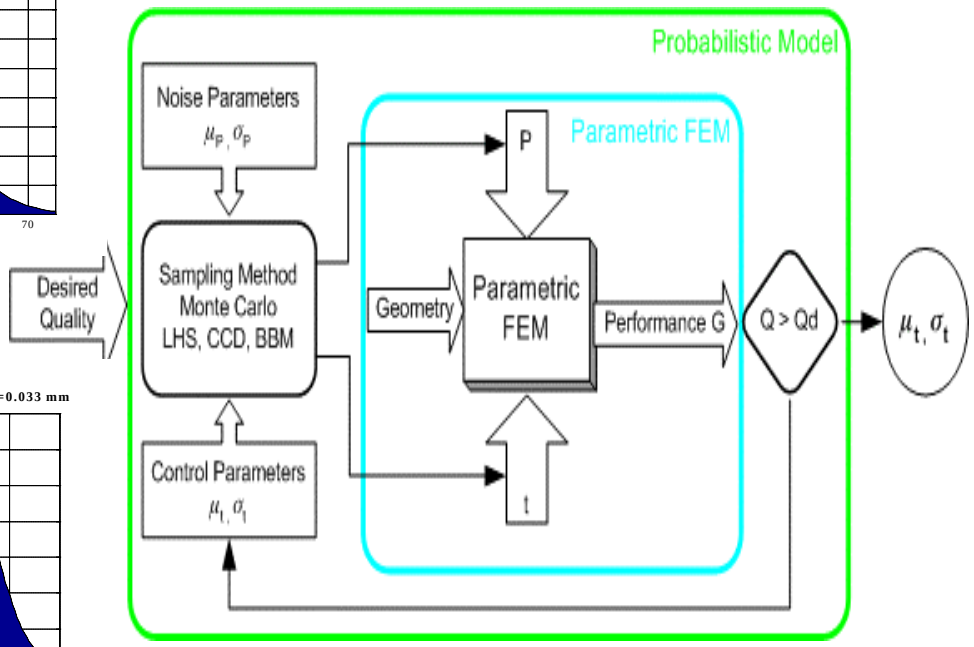
- μ_D = 7.39
- μ_H = 7.00

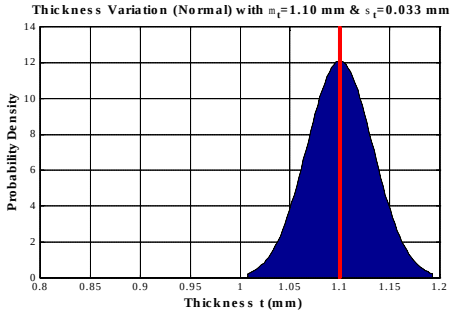


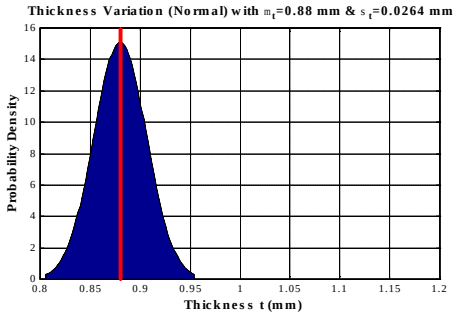
Example # 5 Reliability Based Optimization within Pro/Engineer

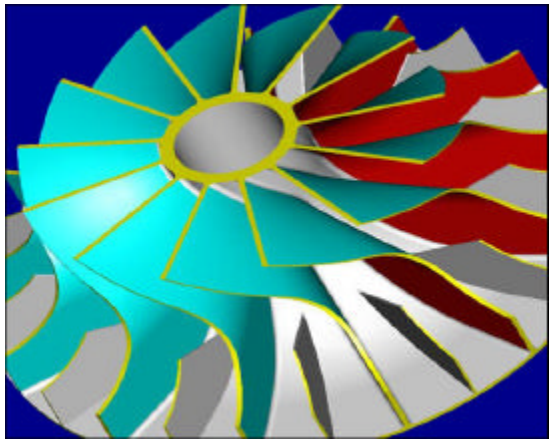


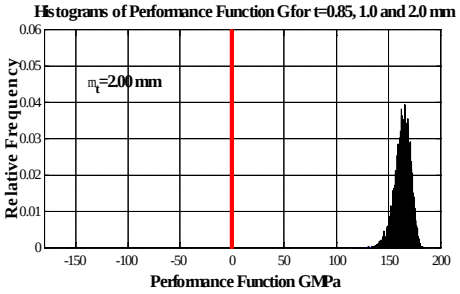

Histogram of Load Variation (Lognormal)
Relative Frequency
Load (N)

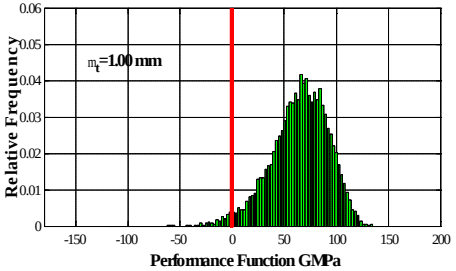

Probabilistic Model
Noise Parameters
μ_P, σ_P
Sampling Method
Monte Carlo
LHS, CCD, BBM
Control Parameters
μ_t, σ_t
Desired Quality
Parametric FEM
P
t
Geometry
Parametric FEM
Performance G
Q > Qd
μ_t, σ_t

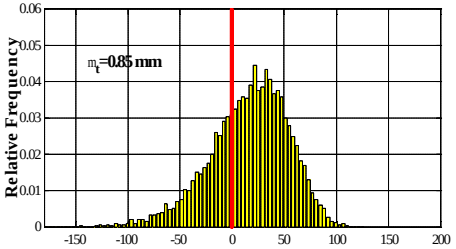

Thickness Variation (Normal) with m_t=1.10 mm & s_t=0.033 mm
Probability Density
Thickness t (mm)

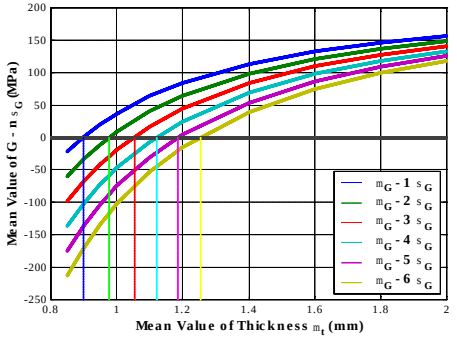

Thickness Variation (Normal) with m_t=0.88 mm & s_t=0.0264 mm
Probability Density
Thickness t (mm)

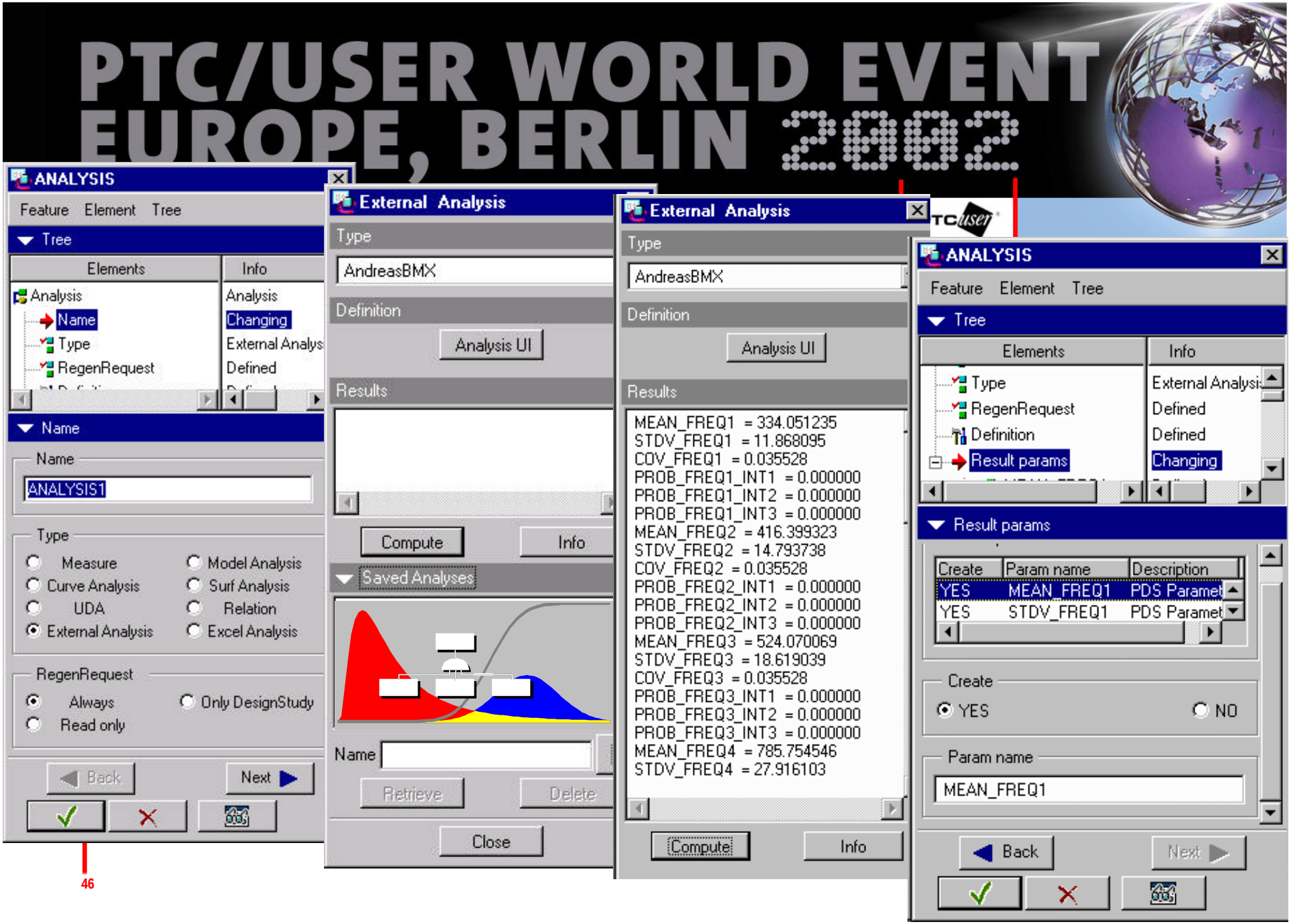



Histograms of Performance Function G for t=0.85, 1.0 and 2.0 mm
m_t=2.00 mm
Relative Frequency
Performance Function GMPa


m_t=1.00 mm
Relative Frequency
Performance Function GMPa

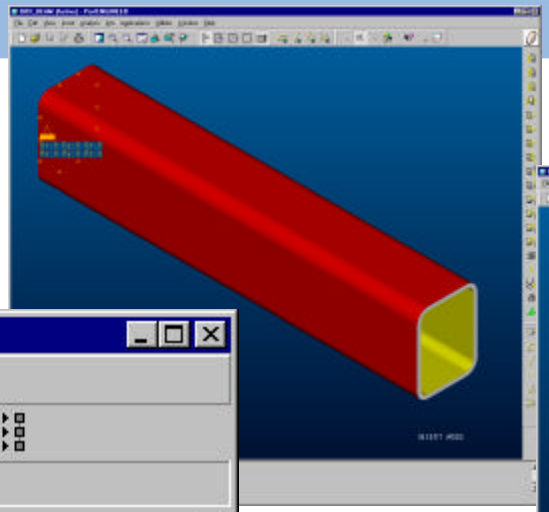

m_t=0.85 mm
Relative Frequency

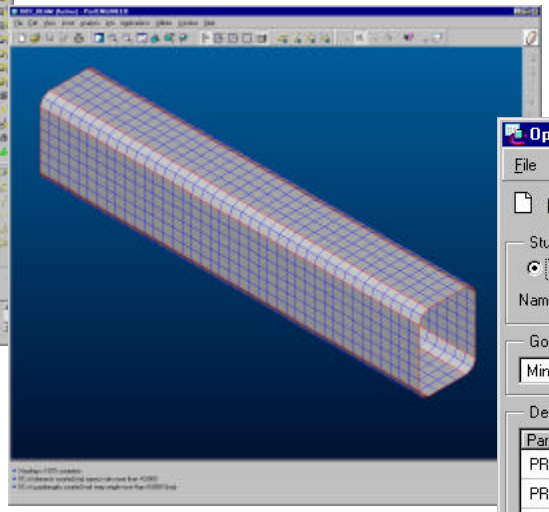

Mean Value of G - n s_G (MPa)
m_G - 1 s_G
m_G - 2 s_G
m_G - 3 s_G
m_G - 4 s_G
m_G - 5 s_G
m_G - 6 s_G
Mean Value of Thickness m_t (mm)

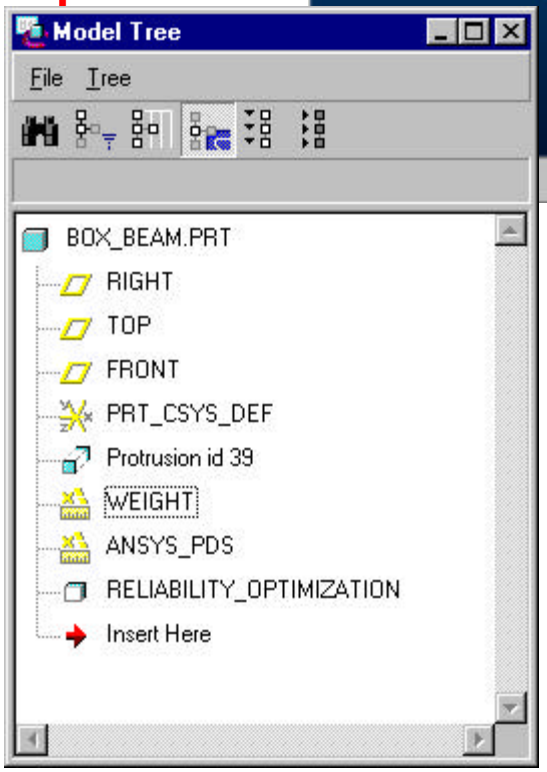

PTC/USER WORLD EVENT
EUROPE, BERLIN 2002
ANALYSIS
Feature Element Tree
Tree
Elements
Info
Analysis
Name
Type
RegenRequest
Changing
External Analys
Defined
Name
ANALYSIS1
Type
Measure
Curve Analysis
UDA
External Analysis
Model Analysis
Surf Analysis
Relation
Excel Analysis
RegenRequest
Always
Read only
Only DesignStudy
Back
Next
External Analysis
Type
AndreasBMX
Definition
Analysis UI
Results
Compute
Info
Saved Analyses
Name
Retrieve
Delete
Close
External Analysis
Type
AndreasBMX
Definition
Analysis UI
Results
MEAN_FREQ1 = 334.051235
STDV_FREQ1 = 11.868095
COV_FREQ1 = 0.035528
PROB_FREQ1_INT1 = 0.000000
PROB_FREQ1_INT2 = 0.000000
PROB_FREQ1_INT3 = 0.000000
MEAN_FREQ2 = 416.399323
STDV_FREQ2 = 14.793738
COV_FREQ2 = 0.035528
PROB_FREQ2_INT1 = 0.000000
PROB_FREQ2_INT2 = 0.000000
PROB_FREQ2_INT3 = 0.000000
MEAN_FREQ3 = 524.070069
STDV_FREQ3 = 18.619039
COV_FREQ3 = 0.035528
PROB_FREQ3_INT1 = 0.000000
PROB_FREQ3_INT2 = 0.000000
PROB_FREQ3_INT3 = 0.000000
MEAN_FREQ4 = 785.754546
STDV_FREQ4 = 27.916103
Compute
Info
TCuser
ANALYSIS
Feature Element Tree
Tree
Elements
Info
Type
RegenRequest
Definition
Result params
External Analysis
Defined
Defined
Changing
Result params
Create
Param name
Description
YES
MEAN_FREQ1
PDS Paramet
YES
STDV_FREQ1
PDS Paramet
Create
YES
NO
Param name
MEAN_FREQ1
Back
Next

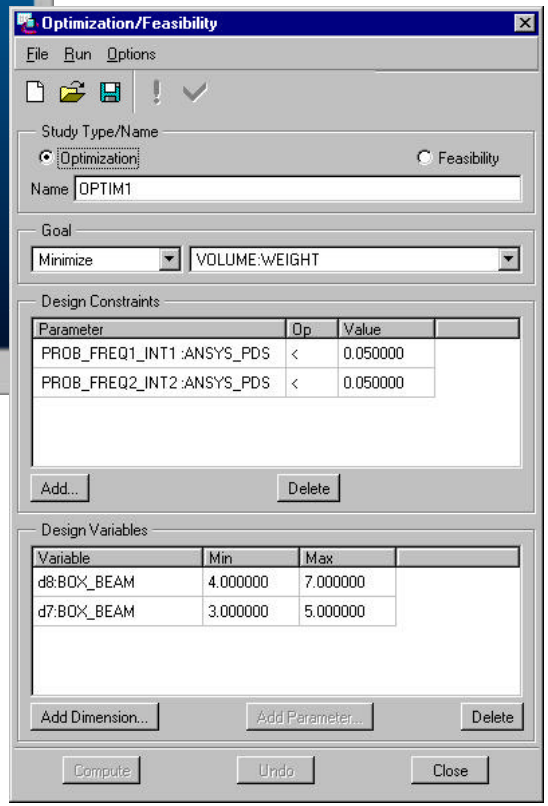
PTC/USER WORLD EVENT EUROPE, BERLIN 2002

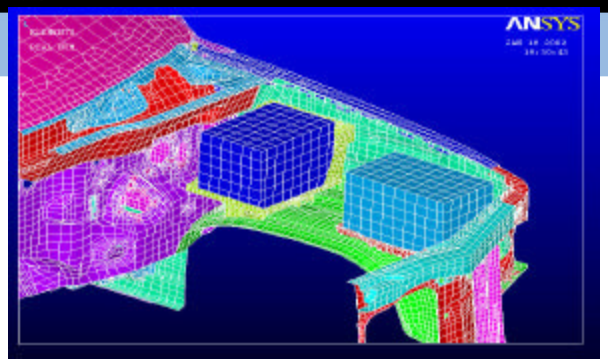
PTC user

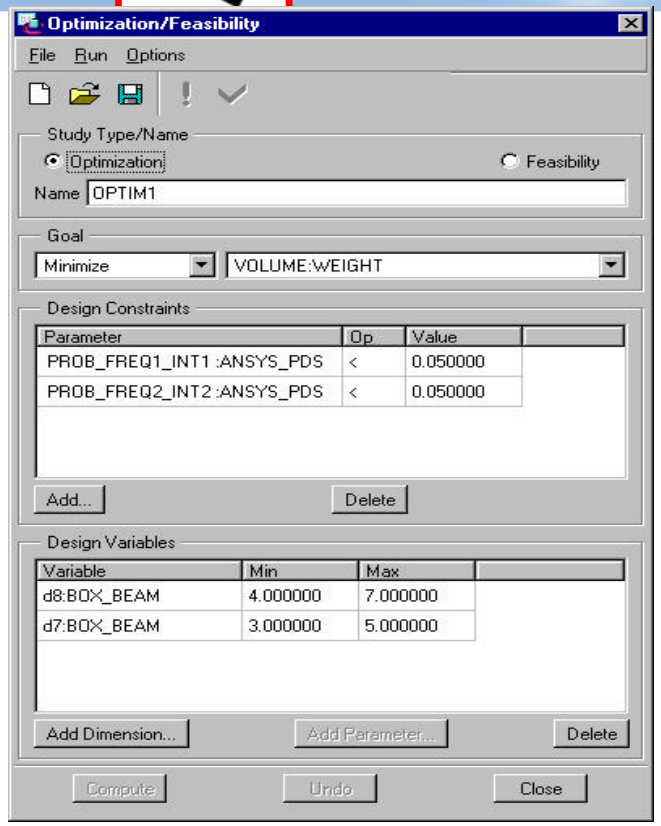


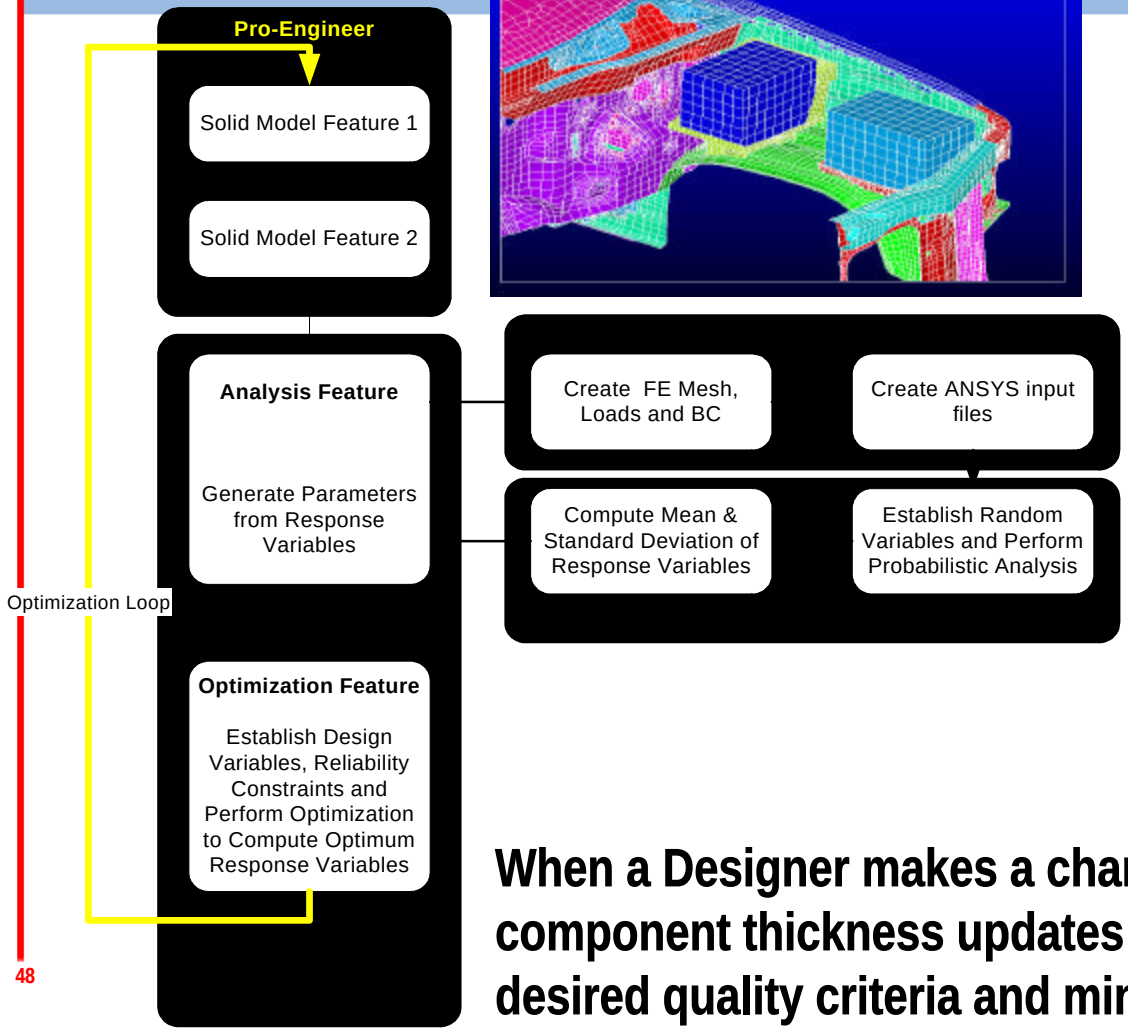












When a Designer makes a change (i.e. hole diameter) the component thickness updates automatically to meet desired quality criteria and minimize weight

Outline

- A status of the current design and simulation state in the product development process
- Overview of the tools and techniques for traditional and robust design (DOE, PDS, BMX, Six-sigma, design synthesis, etc)
- An overview of the “Engineering Quality into the Design”
- Implementation examples of Behavioral Modeling
- Overview of the implementation challenges and solution strategies to overcome them

Why not realizing the expected gains from a CAD & CAE integration?

Technical challenges

- Design process remains unstructured or unplanned
- Insufficient number of experts for product design & attribute prediction
- Product attributes have not been formalized and managed early enough
- CAD / CAE toolset is not tailored to design environment
- Data not readily available to feed analysis

Why not realizing the expected gains from a CAD & CAE integration?

Organizational challenges

- Lack of clear metrics and success stories
- Achieving consensus on methods to be used and on integration of product development environment with PDM software
- Developing and implementing custom capabilities with commercially available software (BMX, Visual DOC, iSIGHT,AI*workbench,CO,…)
- Organization's commitment to product development excellence

Realizing The Expected Gains

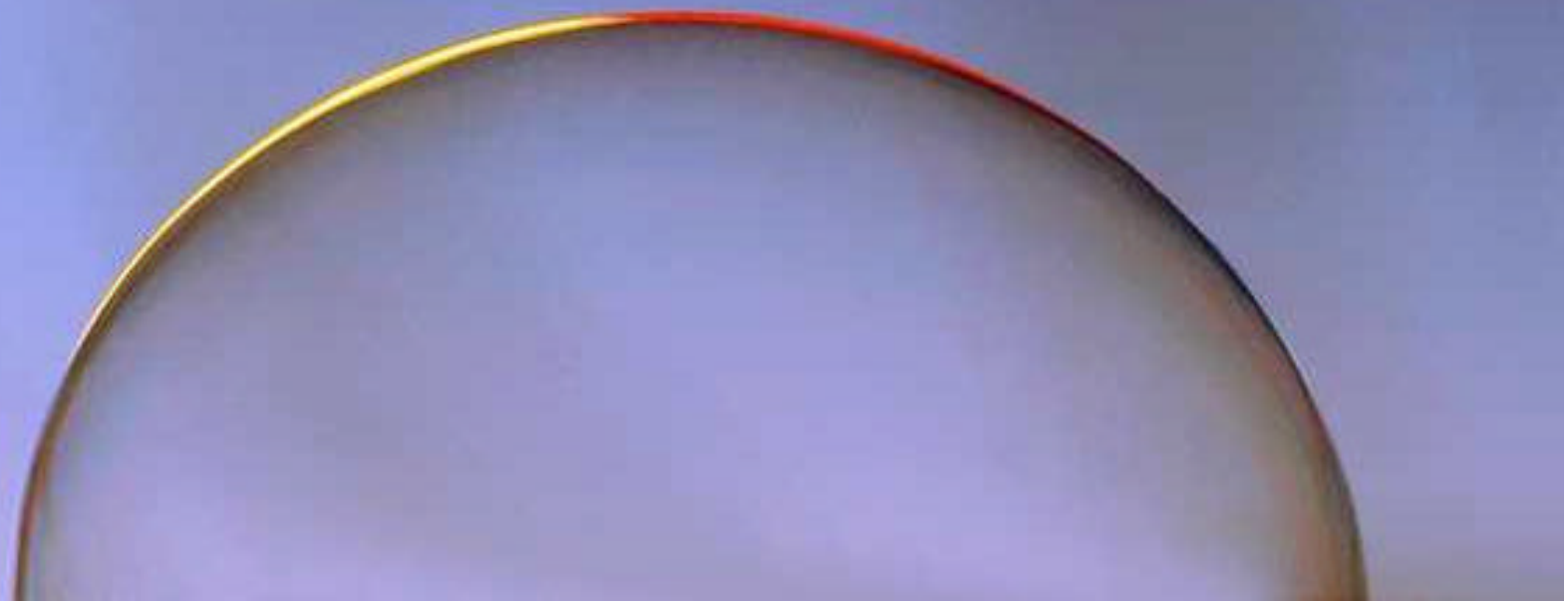
1. Identify the right organization

- Committed to product development
- Willing to change
- Able to make decisions
- Willing to bypass consensus where needed

2. Identify the right project

- Repetitive and measurable
- High value added
- Bottle neck, short duration (3-6 months)
- Non trivial, expertise required
- Mainly with objective requirements

3. Solution Strategies

- Clarify and document the desired design decision process
- Establish the cost & time of the current state
- Create a design environment tailored to the desired design process; workflow management
- Develop a repository of design & manufacturing rules to govern the design process
- Augment the experts by automating large portions of the design process (BMX)
- Simplify and automate tool usage for standard analyses
- Improve attribute prediction as knowledge increases
- Automate data integration and allow for new methods

Create a Vision,
Adopt it,
Adapt to Achieve it